COMPREHENSIVE STUDY
OF
MUD CRACKS
AND OTHER SIMILAR STRUCTURES

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Introduction

In textbooks¹ of geology and in most papers² dealing with geologic structures, mud cracks seem to have been regarded as merely one kind of structure developed only in soft sediments, such as muds or clays. It seems also that the studies of mud-crack structure have been mostly confined to the regions where river flood deposits or littoral deposits occur, and to the margins or exposed parts of lakes, swamps and ponds where desiccation is effective. Furthermore most of the studies of mud-crack structure seem to have considered only two dimensions and do not include the comparison of the cracks or blocks bounded by cracks developed in soft sediments with analogous structures found in rocks other than soft sediments.

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¹ Including many well known books, such as by J.D. Dana, T.C. Chamberlin and R.D. Salisbury, W.B. Scott, A.W. Graban, L.V. Pirsson and C. Schuchert, Sir A. Geikie, and others.

² Contained in the Bibliography at the end of this paper.

As the investigations are limited in this narrow field the mud-crack structures seem not to have been recognized as playing an important role in geologic structures, except where it is used to identify the continental origin of the deposits in which it occurs, or the tops of beds,

In recent years, however, some investigators³ have attempted a broader study of mud-crack structures and applied the name "mud cracks" or "sun cracks" to the analogous and related structures developed in rocks other than the soft sediments. Also some writers have shown that columnar structure and sun cracks or mud cracks are strikingly similar⁴ and sometimes have the same origin due to tension, and that prismatic structures may be produced by expansion, which forms the weather-crack structure in some igneous rocks.⁵

If the study of mud-cracks is broadened so as to cover all their analogous and related structures in spite of the restriction of the sense of the word "mud", it is evident that this mud-crack structure may include many structures

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³ Wherry, E.T. Apparent sun-crack structures and ringing-rock phenomena in the Triassic diabase of eastern Pennsylvania; Acad. Nat. Sci. Phila., Pr. 64, 1912, pp 169-172. Sosman, R.B., Two subordinate types of prismatic structure; Wash. Acad. Sci., Jour. 5, 1915, pp 490-491. Brown, C.B., On some effects of wind and sun in the desert of Tumbez, north-west Peru; Geol. Mag., vol. 61, 1924, pp 337-339.

⁴ Sosman, R.B., Types of prismatic structure in igneous rocks, Jour. Geol., vol. 24, 1916, pp 215-234. Kindle, E.M., Columnar structure in limestone; Can. Geol. Sur., Mus. Bull., no. 2, Geol. Ser. no. 14, 1914.

⁵ Wherry, E.T., op.cit., Sosman, R.B., op.cit.

which are separately described under different headings in geologic literature. The terms mud cracks, sun cracks, desiccation fissures, etc., are interchangeable. Owing to its conspicuousness in the mud this structure is often called mud cracks. But it is true that mud-crack structures or structures similar to the mud cracks occur in nearly all kinds of rocks; igneous or sedimentary, hard or soft.

In regard to the attitude of the cracks and the form of the blocks bounded by cracks, nearly all the structures under the names other than mud cracks are substantially identical to the mud-crack structure, though some may be different in origin or may be more or less variable in form owing to the additional action of some other processes. If mud-crack structure is considered in three dimensions, some of the blocks cut by the cracks extending not far downward are very much like the sheet structure developed in hard rocks, igneous or sedimentary, and some bounded by the cracks going down to a great depth are quite similar to the prismatic or columnar structure. Notwithstanding the different origin and conditions of the formation, the form of the blocks bounded by mud cracks is sometimes identical to that of the so-called stylolites. It is interesting to bring out here Hopkin's statement on stylolites⁶; that the variation in the appearance of the stylolites at different localities, may be correlated with different agencies of formation. Some

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⁶ Hopkins, T.C., Stylolites; Am. Jour. Sci., 4th ser., vol. 4, 1897, pp 142-144.

of them are evidently mud cracks caused either by the sun or by frost. In the advanced stage of the process by which mud-crack structure is formed in hard rocks there may result a concentric structure or exfoliation-crack structure which is of the same origin and form in the incipient stage of formation as mud-crack structure,

In spite of the exaggeration and unnaturalness of the correlation of some kinds of structures, it is interesting to gather all the analogous and related structures to compose a single piece of perspective picture and the term "mud-crack structure" will be used to cover all of them. This paper is prepared for this purpose. The ordinary mud cracks will be taken as composing the basis of the study, and the attempt will be made to compare their analogous and related structures with them and to enlarge the field which the study of the mud-crack structure covers by adding the analogous structures. Some of the related structures should be recognized as varieties of the mud-crack structure, which are different either in origin or form.

Definitions of the Terms Representing Mud Cracks and their Analogous and Related Structures.

Mud Cracks.

Geologic text-books state that mud cracks occur where soft muds spread over flood-plains or composing the bottoms of playa lakes or pools, and left exposed by the recession of the water, dry and break into blocks of irregular outline. The shape of mud cracks varies with the composition of the muds in which they occur and the topographic and climatic conditions under which they are formed.

Owing to this conspicuous occurrence in muds the cracks are called mud cracks. However, there are analogous structures which are not confined to the mud deposits but occur in many kinds of rocks. Thus it seems expedient to use a slightly different term, mud-crack structure, to include not only mud cracks, but also their analogous and related structures. The term mud cracks may then be used to represent merely the cracks formed in muds.

Sun Cracks. The terms, sun cracks and mud cracks are used interchangeably in the literature. However, the former implies a formation by sun-baking and is evidence that the strata have been exposed to the atmosphere at intervals during their deposition¹. The term, mud cracks, does not

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¹ Geikie, A., Textbook of Geology, 4th ed., vol. 1, London 1903, p. 643.

necessarily imply such exposure. Sometimes the mud cracks occur under water and may be due to freezing of the ground². Moreover sun cracks may denote the analogous structures formed in hard rocks³. The heating from the sun may break hard rocks as well as muds, so that all the cracks there developed may be called sun cracks. Where the cause of the breaking is not known, the comprehensive term, mud-crack structure is preferable.

Desiccation fissures⁴ or cracks⁵. The terms, desiccation fissures or cracks, and mud cracks or sun cracks, are often used interchangeably in geological textbooks. These structures are formed by the drying out of muds or soft sediments. Strictly, the term desiccation cracks is interchangeable with mud cracks rather than with sun cracks, for the latter may include also the cracks developed in hard rocks, whereas the desiccation cracks seem to be confined to the soft and moist deposits. But where the mud cracks remain open under water the term desiccation cracks is not applicable.

Frost cracks. Frost cracks compose one type of mud cracks which are due to frost action. The cracks may be formed in two ways; some of large dimensions being produced by hard

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² Moore, E.S., Mud cracks open under water; Amer. Jour. Sci., 4th ser., vol. 38, 1914, pp 101-102.

³ Wherry, E.T., Apparent sun-crack structures and ringing-rock phenomena in the Triassic diabase of eastern Pennsylvania; Acad. Nat. Sci., Phila., Pr. 64, 1912, pp 169-172.

⁴ Lahee, F.H., Field Geology, 1st ed., N.Y., 1916, pp 52-53.

⁵ Geikie, A., op. cit.

frost at a very low temperature⁶; others of small size being formed by the action of freezing⁷ water contained in the mud. The first type is exactly similar to that produced by desiccation in mud, whereas the second is somewhat different from the desiccated mud cracks. The frost cracks are developed in soft deposits and found in rather cold regions.

Insolation joints. At times the term, insolation joints, is used to denote mud-crack structure, especially with reference to cracks developed in hard rocks. It may, however, be defined in the same way as sun cracks. Because the insolation⁸ is caused by the changes of temperature in rocks or sediments due to the sun, it seems illogical to differentiate the cracks formed by sun-baking from the cracks developed by insolation. The insolation joints may be formed either in hard rocks or in soft deposits.

Weather cracks or weather-crack structure⁹. This is one type of the prismatic structure. The cracks are common in hard rocks and may be due to internal expansion. As indicated by the word weather, the cracks are apparently formed by weathering. Because this structure is formed under the same conditions as sun cracks or mud cracks, (namely those of weathering), and

⁶ Leffingwell, E. de K., The Canning River Region, northern Alaska: U.S. Geol. Surv., Prof. Paper 109, 1919, pp 205-211. Hawkes, L., Frost action in superficial deposits, Iceland: Geol. Mag., vol. 61, 1924, pp 509-513.

⁷ Udden, J. A., Fossil frost cracks: Sci Am., vol. 72, 1895, p 102.

⁸ Van Hise, C. R., A Treatise on Metamorphism: Mon. 47, U.S. Geol. Surv. 1904, p 437.

⁹ Sosman, R. B., Types of prismatic structure in igneous rocks; Jour. Geol., vol. 24, 1916, pp 230-231.

has the same shape as prismatic structure, it may be regarded as the basis for gathering sun cracks and prismatic structure, etc., under the general heading "mud-crack structure".

Shrinkage¹⁰ cracks or joints. This term is often used to denote mud-crack structure. Where the clay particles are of uniform size and are drying evenly, the shrinkage cracks are arranged in regular patterns, such as occur in some cooling lavas. The sudden cooling of the molten magmas in contact with the cold wall-rocks may result in the formation of hexagonally arranged shrinkage cracks. In short shrinkage cracks are due to the contraction of the rocks, and may be produced either by the drying of soft deposits or by the cooling of igneous magmas. It is clear that the term shrinkage cracks may also be used in grouping some similar structures under one general heading.

Contraction joints¹¹. The terms contraction joints and shrinkage cracks, are interchangeable. Some classifications group all joints into two classes, contraction joints and expansion joints. Contraction joints are likely to be non-parallel and non-intersecting, dividing the rocks into irregular polygonal blocks which are analogous to those bounded by mud cracks, whereas expansion joints are commonly parallel to the surface of the rock mass.

Sheet structure¹². Under weathering the upper surface of some rocks may be subject to some agencies, especially

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¹⁰ Blackwelder, E., Elements of Geology, 1st ed., N.Y., 1911, p 5-6. Crosby, W.O., The Classification and origin of joint structures: Am. Assoc. Adv. Sci., Proc. 31, 1883, p 409. Leith, C.K. Structural Geology, revised ed., N.Y., 1923, p 50. Twenhofel, W.H., Treatise on sedimentation, 1st ed. Baltimore, 1926, p 492. Walling, H.F., The origin of joint cracks, Am. Assoc. Adv. Sci., Proc 31, 1883, p 417. Wherry, E.T., op cit.

¹¹ Crosby, W.O., op.cit.

¹² Dale, T.N. The commercial granites of New England. U.S. Geol. Sur.

especially sun-heating, which form horizontal joints dividing parts of the rocks into sheet-like blocks, usually of variable dimensions. This is often called sheet structure. It occurs either in granites or in sandstones and is probably due to expansion of the rocks. This structure is often associated with vertical joints which may be due to tension. In such cases some of the blocks bounded by horizontal and vertical joints are similar to those formed by shallow mud cracks in soft deposits. The blocks are likely to be polygonal in form.

Tabular structure¹³. This term may be interchangeable with sheet structure, but denotes structures of smaller dimensions. In many igneous rocks the horizontal joints are so regularly and strongly defined as to produce a bedded or tabular structure which is roughly parallel to the bounding surface of the mass, as is also the bedding in some cases, where associated with columnar structure in igneous rocks, this structure may result in the formation of polygonal blocks like those bounded by mud cracks. If the horizontal joints are closely spaced the structure becomes finer and may be called platy structure, which is much finer than the structure formed by mud cracks.

Columnar or prismatic structure¹⁴. Some rocks have a remarkably perfect system of cross-jointing that divides the rock mass into columns or prisms, from which the name of this structure is derived. The columns or prisms may have a variable

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Bull 738, 1923, p 26. Leith, C.K., op.cit., pp 54-57.

¹³ Bonney, T.G., On Columnar, fissile and spheroidal structure; Quart. Jour. Geol. Soc. London, vol 32, 1876, pp 145-146.

¹⁴ Many papers and books dealing with this subject, contained in Bibliography.

number of sides, but most commonly they are hexagonal. Some have wonderful regularity of form. This structure usually occurs in the igneous rocks composing intrusive sheets, dikes and flows. Because it is especially developed in basalt, this structure is often called basaltic jointing or parting. The columnar structure is developed not only in the igneous rocks but also in some sedimentary rocks, such as sandstone and clay. Where mud cracks are well developed and extend downward, they may result in the formation of the blocks very much like columns, so that it seems not unreasonable to correlate this structure and mud cracks and to group them under the general heading "mud-crack structure".

Stylolites¹⁵. In some compact sedimentary rocks there occurs a peculiar jointed or columnar structure whose origin has long been in doubt. The structure consists of a series of alternating, inter-penetrating columns of rock called stylolites. These form the irregular, interlocked suture in sections at right angles to the bedding planes. The stylolites are composed of the same material as that of the rock in which they occur. This structure was first noted by Mylius, in 1751, who described stylolites as "Schwielen". Thereafter investigators

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¹⁵ Stockdale, P. B., Stylolites; their nature and origin; Indiana University Studies, Study no. 55, 1922. Marsh, O. C. Origin of the so-called Lignilites or Epsomites: Am. Assoc. Adv. Sci., Proc. 16, 1868, pp 135-143. Gordon, C. H., On the nature and origin of the stylolitic structure in Tennessee marble: Jour. Geol., vol. 26, 1918, pp 561-568. Many other papers dealing with this subject are contained in the Bibliography.

used various names for this structure, such as lignilites, epsomites, crystallites, suture joints, crow-feet or toe-nails, etc. The term stylolite (from the Greek stulos, meaning column) was given by F. Klöden and is now generally accepted. The German terms "Drucksuturen" (pressure suture) and "Stylolithen" are used by some scientists to denote analogous or related structures. The structure is well developed in limestone, marble and dolomite, and also occurs in quartzite and shale. Because of their columnar shape, stylolites are considered as one of the mud-crack structures, though their origin may be quite different from that causing prismatic structure or mud cracks. Hopkins¹⁶ states that some stylolites are evidently mud cracks caused either by the sun or by frost.

Curvitar structure¹⁷. In places, rocks are traversed by a series of more or less horizontal curving joints with their convexities upward, so that the whole is divided into a series of plano-convex, meniscoid, or concavo-convex blocks. This is called curvitar structure by some geologists. The structure differs from sheet structure in that the joints are always curved and the blocks formed have convex top sides and concave bottom sides. It often occurs in association with vertical joints, and may become rudely columnar where the space between adjacent horizontal joints is wider than that between adjacent vertical joints. This structure is well developed in basalt.

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¹⁶ Hopkins, T.C., Stylolites; Am. Jour. Sci., 4th ser., vol 4, 1897, pp 142-144.

¹⁷ Bonney, T.G., op.cit., pp 146-147.

Cup-and-ball structure¹⁸. In the columnar structure the columns may be divided by a series of cross joints; where the joint-surface is not a plane but more or less so curved that the convex extremity of one segment fits into the concave extremity of the next, the cup-and-ball structure is formed. Where the curvature of the joints is but slight, they continue to the sides of the columns. Where the curvature is more marked, and the joints do not continue to the sides of the columns, the outline of the ball is more nearly circular. The curves generally point in one direction, sometimes upward, sometimes downward; occasionally, however, they are differently directed in adjoining columns. This structure also often occurs in basalt where it seems to be a combination of columnar structure and well-developed curvilinear structure.

Concentric structure¹⁹. Some weathered rocks, particularly homogeneous igneous rocks such as granite, are so cracked that the rocks tend to spall off at the surface in concentric shells, leaving the unweathered or less weathered inner part of rock mass as boulders. This is often called concentric structure. Though the resulting blocks are different in shape from those formed by mud cracks, the polygonal cracks developed during the incipient stage of the process are just the same as those forming the mud blocks. The former differ from the latter in that they tend

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¹⁸ Bonney, T.G., op.cit., pp 147-149.

¹⁹ Blackwelder, E., Exfoliation as a phase of rock weathering; Jour.Geol., vol.33, 1925, pp 793-806. Leith, C.K., op. cit., p 49.

to develop laterally and more or less parallel to the surface of the rock mass in advanced stages of the process. During the process of cooling in some igneous rocks, or in some rocks in contact with them, complex jointing may be formed which locally is concentric about loci of cooling. This may be called a special form of columnar structure.

Exfoliation cracks²⁰. This term and concentric structure are sometimes used interchangeably. But exfoliation cracks include only the results of rock weathering, i.e., are formed by exfoliation due to weathering processes. In typical exfoliation a series of cracks is formed, roughly concentric to a single joint-block. The surface portion of the rock mass is subject to a series of strains which will result in the flaking or peeling off of such outer layers. As the angles of rock mass are most exposed, they will spall off first, and the result will be the production of a curved or rounded outline, and the subsequent layers peeled off will also be curved. Thus concentric exfoliation or the successive peeling off of the layers of rocks results.

Spheroidal structure²¹. This term and concentric structure may be used interchangeably. But the former has been recognized by some geologists in rocks which are not

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²⁰ Blackwelder, E., op.cit. Branner, J.C., Bull, vol. 7, 1896, Decomposition of rocks in Brazil; pp 269-280. Graban, A.W., A Textbook of Geology, Part 1, 1st. ed. N.Y., 1920, pp 393-398.

²¹ Bonney, T.G., op.cit., pp 149-154. Thomson, J., Report of Belfast Naturalists' Field Club, 1869-1870 (cited by Bonney).

necessarily homogeneous and probably exists independently of the presence of dividing cross joints. Some investigators regard the spheroidal structure as the result of a process of exfoliation due to action of the weather on a regular-shaped homogeneous mass, while others maintain that this structure is in no way to be explained by simple exfoliation during decomposition, but that the contraction of a cooling mass should be considered as being an important factor. This structure occurs in various rocks such as shales, volcanic ash and obsidian, though, in the latter it exists in a minute scale, and is called perlitic structure.

Types of the mud-crack structure.

Mud crack structures may be classified according to the form and size of the blocks (or the distribution of the joints) or according to the conditions of origin. As all the factors governing the formation of the structure are not known, it seems better to base a comprehensive classification on the shape and size of the structure.

In the formation of the mud-crack structure many sets of cracks arranged either regularly or irregularly, cut the rock mass into different kinds of blocks. Under different conditions the cracks may be so arranged as to form patterns ranging from simple to very complex. One set of approximately parallel cracks may cut the rock mass into vertical ribbon-shaped strips or into horizontal sheets. Two or more sets of cracks may separate the rock mass into rhomboidal or polygonal blocks, where the cracks are confined superficially, or into columns or prisms, where they extend far downward or inward from the surface of the rock mass. Where the cracks form curved or very irregular surfaces, many varieties of resulting blocks are formed. So, according to the nature of the cracks and the resulting blocks, the mud-crack structure may be classified as the parallel, the polygonal, the columnar, and the spheroidal structure.

Parallel mud-crack structure.

Under this heading will be noted some special kinds of structure which may be regarded as formed in the incipient stages

of the development of the mud-crack structure or as being an incomplete type of it occurring under certain conditions, though this kind of structure does not exactly resemble the usual mud-crack structure. This has been found in mud and in some hard rocks, igneous and sedimentary. Some types are called parallel mud cracks or parallel cracks; others are known as sheet structure. But these two kinds of structure are different in attitude; the parallel cracks are approximately vertical, whereas the sheet structure is nearly horizontal.¹

Parallel cracks in mud do not seem to have been considered before Kindle's² experimental study ten years ago. He tried to produce parallel mud cracks in a shallow pan of 11 inches in diameter. A mixture of one part of Lake Ontario clay and five parts of fresh water was put in the pan, without exposure to the sun. One side of the pan was raised 0.1 of an inch higher than the opposite side. The lower side remained moist while the upper side dried, and the cracking began on the upper side. The cracks thus formed were approximately parallel (fig. 1). So he concludes that approximate parallelism of mud cracks may result from zonal drying of the mud. But later experiments performed under apparently the same conditions failed to produce parallel mud cracks. Experiments conducted by Dr Twenhofel³ in a large tank did not support this generalization, and Doerr's

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¹ Dale, T.N., The commercial granites of New England: Bull. 738, U.S. Geol. Sur. 1923, p 26.

² Kindle, E.M., Some factors affecting the development of mud cracks: Jour. Geol., vol. 25, 1917, pp 135-144.

³ Twenhofel, W.H., Treatise on Sedimentation. 1st. ed., Baltimore 1926, p 495.

experiments⁴ indicate that mud cracks formed on inclined surfaces, display no tendency toward parallelism. The writer has tried to produce parallel mud cracks several times but without success. MacCarthy⁵ observed mud cracks formed on steeply inclined surfaces, but parallel mud cracks are not included in his descriptions. In short, it appears that the conditions favoring the development of parallel cracks in mud are not yet known.

The parallel cracks in hard rocks have been found to be produced by insolation. In the desert of Tumbes, North-west Peru, Brown⁶ observed an andesite pebble having a series of parallel cracks which show a tendency toward parallel development, though the cracks are somewhat curved and branching (fig.2). The structure looks very like that produced by Kindle's experiment in mud (compare fig.1 and fig.2).

Sheet structure is commonly observed in some stone quarries and has long been studied by geologists. It commonly occurs near the weathered surface in granite and sandstone. The sheets formed by the fractures or cracks tend to parallel the rock surface whether this is horizontal or inclined.⁷ The cracks are generally approximately parallel, but where the sheets are lenticular they may be undulating in such a way that only every other set is parallel⁸ (fig.3),

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⁴ Doerr, J.E., Investigation of the Character of mud cracks; thesis, Univ. of Wis., 1924; An investigation of the characteristics of mud cracks; thesis, 1926.

⁵ MacCarthy, G.R., Mud cracks on steeply inclined surfaces; Jour. Geol., vol 30, 1922, p 702.

⁶ Brown, C.B., On some effects of wind and sun in the desert of Tumbes, north-west Peru; Geol. Mag., vol. 61, 1924, pp 337-339.

⁷ Leith, C.K., Structural Geology, revised ed., N.Y., 1923, p 54.

⁸ Dale, T.N., op. cit., p 32.

The parallel cracks in hard rocks are very small in size and limited to the surface, as stated in the Peru case. The cracks forming sheet structure are generally curved and more or less undulating, and extend laterally. The individual cracks may reach several tens of feet in length, and may be interrupted by vertical joints or by contiguous joints. They are not widely spaced, nor branched. The sheets are thinnest near the surface and rapidly thicken below,⁹ and this downward increase in the thickness of the sheets is generally more rapid where the texture of the rock is coarser.¹⁰ The thickness of the sheets varies from a few inches near the rock surface to about 60 feet at a depth of 105 feet at the Hurricane Island quarry¹¹. The sheets are generally lenses distributed so that the tapering end of one lens lies between the thickest parts of two others. The sheets are commonly crossed by vertical joints, and where two or more intersecting sets of vertical joints occur, polygonal blocks result (fig 4).

Polygonal mud-crack structure.

Polygonal mud-crack structure includes most, if not all, of the mud cracks, frost cracks, insolation joints, shrinkage cracks, tabular structures, etc., and also some types of sheet structure which are accompanied by vertical joints. The cracks are devel-

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⁹ Leith, C.K., op.cit. p 54.

¹⁰ Herrmann, O., Steinbruchindustrie und Steinbruchgeologie, 1899, pp 109-111 (cited by Dale).

¹¹ Dale, T.N., op.cit., p 32.

oped in such a way that they tend to form a network cutting the rock surface into polygons. Although the typical parallel, polygonal and columnar structures are readily distinguished, there are intermediate forms which are difficult to classify. Some sheet structures have vertical joints and some columnar structures have horizontal joints which divide the rock masses into blocks, resembling those of the polygonal structure. However, in both of these cases the blocks are piled tier upon tier, whereas those in the typical polygonal structure form only one layer, though they may occasionally form several layers where the cracks normal to the surface are unusually deep. For clearness the writer has adopted an arbitrary classification for these intermediate structures which places among the polygonal structures those with blocks having their cross-sectional or polygonal diameters greater than their length, and places with the parallel or sheet structures those with no well-marked prismatic jointing normal to the sheets. However, where a polygonal structure has the joints normal to the surface extending far inward into the rock mass, or where a columnar structure is traversed by closely spaced cross joints, the two structures are of identical form.

The attitude, dimensions and form of the cracks and polygons are different not only in various individual structures but also in the same structure. Under different conditions or environments and in various kinds of rocks the cracks and polygons may vary within wide limits in dimensions and shape. There are many factors which govern the formation and development of the polygonal structure, and each individual structure shows the control of certain factors to which its special nature is due, so

that it seems advisable to describe the nature of the cracks and polygons of some typical localities.

The term mud cracks is used here to denote the cracks developed in mud or soft deposits. At a certain stage in the desiccation of the mud the cracking begins. According to observational and experimental study the cracking appears to start at the places of greatest weakness. A buried stick or a sandy spot, the presence of a hole, or any occurrence weakening the mud leads to the development of cracking at that place¹². The various cracks develop in different directions and their crossing defines the polygons. There seems to be a general tendency for the cracks to bend. With unequal drying on the two sides of the cracks, they may be sharply curved. The cracks which form in the early stages of desiccation are usually the major controlling cracks, and the secondary cracks or those starting out from other cracks usually commence from angles in the cracks or from the convex sides of the cracks.¹³ There may be several cracks radiating from a point, but this is an exception in nature.

The length of a single crack varies within wide limits, from a few inches to several feet, but in the Canning River Region, northern Alaska, the first cracks developed in mud are of much larger size, and some may reach more than 10 meters in length¹⁴.

The spacing of the cracks seems to depend on the rate of drying, the thickness of mud, the character of the water in which the mud was deposited, the nature of the material below, the

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¹² Twenhofel, W.H., op.cit., p493.

¹³ Doerr, J.E., op. cit., thesis, 1926.

¹⁴ Leffingwell, E.de K., The Canning River Region, northern Alaska: Prof. Paper 109, 1919, pp 205-211. U.S. Geol Sur.

presence of foreign matter, and the number of the pre-existing cracks in the area. Slow drying seems to produce comparatively widely spaced cracks, while rapid desiccation gives closely spaced cracks¹⁵. Thick muds of homogeneous character give wider spacing than do muds that are within layers. Marly, limy and sandy muds give a narrow spacing. The cracks developed in water with a high degree of salinity are known to be very narrow: Muds which contain much foreign matter in the form of sticks, bits of straw, etc., give closer spacing than do those in which such material is lacking¹⁶. The more numerous the cracks in a certain area the narrower are the cracks¹⁷.

The width of the cracks ranges from a fraction of an inch to several inches (fig. 6). On the marine beach in Florida the mud cracks (figs. 7 and 8) were observed by Kindle to have minimum and maximum widths of from $\frac{3}{4}$ to 4 inches¹⁸.

In depth the cracks may terminate within a few inches or they may pass downward a few feet. The latter case may be found in the deposits of deltas, flood plains (fig. 6), etc. during long dry weather. Gilbert mentions that mud cracks penetrate ten feet downward into the variegated shales of the Upper Shinarump of the Jura Trias¹⁹ (fig. 9). But where the cracks extend

¹⁵ Doerr, J.E., op.cit., Thesis, 1924.

¹⁶ Twenhofel, W.H., op.cit. pp 493-494.

¹⁷ Doerr, J.E., op.cit. Thesis, 1926.

¹⁸ Kindle, E.M. Notes on mud cracks and ripple mark in recent calcareous sediments: Jour: Geol., vol 31, 1923, pl40.

¹⁹ Gilbert, G.K., Geology of the Henry Mountains: U.S. Geog. G.S. Rocky Mountains Region, 1880, p.9.

downward to a great depth, and form blocks of small area, they are preferably classed as a columnar structure.

The shapes of polygons vary within wide limits. Polygons with three, four, five, or six sides are those most commonly seen. In experiments the maximum number of sides developed on any one polygon was seven. There is no essential equality to the lengths of sides.

The polygons may turn up or turn down at the edges, this ^{to depend} seems on which portion of the cracked mud dries the more rapidly, on the thickness of the mud, and on the character of the water in which the mud was deposited. Blocks which dry more rapidly on top than elsewhere curve upward at the edges; those which dry more rapidly on the bottoms or the margins have the edges turned down; and those which dry at the same rate on the top and bottom remain flat. Thin muds show the greatest turning up at the edges. The extreme case is shown by the mud curling into shallow cylinders²⁰. In water with a high degree of salinity the blocks curve downward, in fresh water they curve upward, and in water with the salinity of ordinary sea water, they retain a flat surface²¹. In describing the mud cracks on the Missouri River flood plains in South Dakota, Ward²² mentions that convex or flat fragments need not always signify a saline mud but that the character of the surface on which the mud is deposited is also a determining factor. In the description of the mud cracks on the beaches in Florida, Kindle notes that the margins of the polygons showed

²⁰ Twenhofel, W.H., op.cit., p 494.

²¹ Kindle, E.M., Some factors affecting the development of mud cracks: Jour. Geol., vol. 25, 1917., pp 135-144.

²² Ward, F., Notes on mud cracks: Am. Jour. Sci., 5th ser., vol. 6, 1923, pp. 308-309.

clearly three or four laminae exposed, the unequal rates of shrinkage having developed terrace-like margins along the fissures²³, (fig.8).

The polygons may be only a few inches across or several feet in diameter. In Florida the polygons were observed to be from 6 inches to $3\frac{1}{2}$ feet in diameter (fig.7). But the exceptional case was found in the Canning River Region, northern Alaska, by Leffingwell, where the largest polygonal block formed by frost cracks in mud is about 36 by 49 feet and the smallest 16 by 26 feet, the average diameter of 11 blocks being about 36 feet²⁴ (fig.5).

The thickness or height of the polygons varies with the depth to which the cracks extend. Where the vertical dimension of the polygons is greater than the diameter of their surface, the polygons become columns and thus are assigned, according to the demarcation here suggested, to the columnar structure.

Two special types of the mud-crack structure may be mentioned here. Some mud cracks remain open under water and others are formed over water. The first type was found by Moore²⁵ in Centre County, Pennsylvania, where the mud cracks occurred on the bottom of a pond. The water was about a foot deep and many of the cracks as much as an inch and a quarter wide. The second type was observed by Willard²⁶ in the Bad Lands in South Dakota. The water of the water holes in some creeks was

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²³ Kindle, E.M., Notes on mud cracks and ripple mark in recent calcareous sediments, op.cit., p 140.

²⁴ Leffingwell, E.de K., op.cit., pp 205-211.

²⁵ Moore, E.S., Mud cracks open under water, Am.Jour.Sci., 4th ser. vol.38, 1914, pp 101-102.

²⁶ Willard, B., Mud cracks forming over water: Jour.Geol.vol.33, 1925 pp 285-287.

covered with a thick, scumlike deposit of fine mud, which cracked due to shrinkage and showed outlines of polygonal fractures, at times even opening to expose narrow lanes of water. This structure is small and quite rare in nature.

The terms, insolation joints or cracks, are used here to denote the cracks which are formed in hard rocks under weathering, such as sun-heating, frost action, etc. But the demarcation between these and those developed due to cooling of molten magmas may sometimes hardly be drawn. The heat of the sun expands the exposed surface of the rock mass during the day, and at sundown rapid radiation causes contraction, forming numerous cracks. The cracks are usually intersecting in such a way as to divide the rock mass into polygonal blocks. The best example was observed by Campbell in the Twentymile Park District, Colorado, where the surface of the Twentymile sandstone weathers into a network of polygons which are separated by cracks²⁷ (figs. 10 and 11). In the desert of Tumbez, north-west Peru, some interesting effects of the sun's heat were found by Brown. On some sandstone pebbles there were formed very fine polygonal cracks (figs. 12 and 13), which penetrate the pebbles²⁸. In Montgomery County, Pennsylvania, the diabase boulders often show on their surface hexagonal cracks (figs. 14 and 15), which are suggested, by Wherry, to be caused by the expansion of the surface layers during the exfoliation of the boulders under the action of frost²⁹.

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²⁷ Campbell, M.R., The Twentymile Park District of the Yampa Coal Field, Routt County, Colorado: U.S. Geol. Sur., Bull 748, 1923, p 8.

²⁸ Brown, C.B., On Some effects of wind and sun in the desert of Tumbez, north-west Peru: Geol. Mag., vol 61, 1924, pp 337-339.

²⁹ Wherry, E.T., Apparent sun-crack structure and ringing rock phenomena in the Triassic diabase of Eastern Pennsylvania; Acad. Nat. Sci. Phil. Proc. 64, 1912, p 170.

The cracks formed in these hard rocks may be curved or straight, irregular or regular, and thus the blocks may be quite regular or irregular in shape. They are likely to have smaller dimensions than those developed in mud; though in the Twentymile Park District the sandstone polygons are known to be one foot or more in diameter and the cracks are an inch or so deep.

The term shrinkage cracks is used to include the cracks which are produced by the cooling of molten magmas. In the course of the intrusion of the magma the outer portions are rapidly chilled by the cold wall-rocks, and solidify in correspondingly fine-grained form; at the same time there develops, perpendicular to the contact surfaces, hexagonally arranged shrinkage cracks. In some rocks this tends to result in the formation of polygonal blocks. In Montgomery County, Pennsylvania, on the surface of the diabase sill which is in contact with some metamorphosed shale beds, there occurs a rudely hexagonal network of cracks, closely resembling some sun-cracks, frequently found in the sediments³⁰ (fig. 16). This type of polygonal structure is regarded as being developed by the cooling of the molten diabase against the shale surface. And, Stose states that the same phenomenon has been seen on the upper contact of diabase sheets in southern Pennsylvania and is regarded as produced by shrinkage or rapid cooling and incipient formation of polygonal blocks³¹.

Tabular structure may be attributed to shrinkage, for some investigators regard it as being due to the contraction of

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³⁰ Wherry, E.T., op.cit., pp 169-172.

³¹ Stose, G.W., Discussion on Wherry's article; Bull. Geol. Soc. Am., vol. 22, 1911, p 718.

a cooling igneous mass. Bonney suggests that all the points lying in a plane parallel to one surface in a body are in a state of uniform strain in one direction and that naturally there would be a tendency to rupture along a surface at right angles to the strain. In the cooling of an igneous mass, where heat is lost from a surface the phenomenon is analogous to this. When cooling takes place uniformly from all the points of a plane surface, then tabular forms would result³². Tabular structure occurs in granites, dolerite and gabbro, and often is associated with columnar structure.

In regard to the formation of sheet structure several causes are suggested; it may be due to expansion caused by solar heat, to contraction in the cooling of igneous rocks, to concentric weathering, or to still other causes. As this structure sometimes occurs in sandstone, it seems clear that it may develop independently of cooling of igneous masses. On the other hand Becker has found the granites and gneisses at the bottom of the Colorado Canyon both vertically and horizontally jointed, which shows that sheet structure may occur independently of solar heat³³. Some sheet structures have marked prismatic jointing crossing the sheets, and are accordingly considered as types of polygonal structures. This type of structure is usually not as regular as the other polygonal structures. Commonly the size of the polygons is larger and the cracks longer than those developed in other types of the polygonal structure, with the exception of those

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³² Bonney, T.G., On Columnar, fissile, and spheroidal structure: Quart. Jour. Geol. Soc. London, vol. 32, 1876, pp 140-154.

³³ Dale, T.N., op.cit., p 29 (cited by Dale)

formed by frost cracks.

Columnar mud-crack structure.

In a way, columnar mud-crack structure can be considered as including the best developed mud cracks and blocks. As stated above, the writer includes as columnar structures those which have the lengths of the blocks greater than the diameters of their cross-sections.

The first type of columnar structure is that formed in mud or soft deposits where the cracks extend downward to a great depth due to certain favorable conditions, such as a long period of desiccation, a high temperature, a high degree of dryness of the air, etc. The mud cracks in the Shinarump shale in Henry Mountains penetrate 16 feet downward into the shale³⁴ (fig. 9). And, in the vicinity of Menomonee, Dunn County, Wisconsin, Salisbury found beautifully developed columnar structure in clay, where columns, varying from ten to sixteen inches in diameter³⁵ were observed to extend downward a number of feet. The heights of the blocks or columns are several times longer than other two dimensions. Kindle found columnar structure in limestone (fig. 17 and 18) and believes that the columns extending to considerable depth are the result of mud cracks which were formed in an arid climate³⁶. Because the cracks were originally formed in soft deposits, they are included here with the columnar

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³⁴ Gilbert, G. K., *Geology of the Henry Mountains*, U. S. Geog. G. S. Rocky Mountain Region, 1880, p. 9.

³⁵ Salisbury, R. D., *Columnar Structure in Subaqueous Clay*; *Science*, vol. 5, 1885, p. 287.

³⁶ Kindle, E. M., *Columnar structure in Limestone*; *Can. Geol. Sur., Mus. Bull. no. 24*, 1914, pp. 1-5. (*Geol. Ser. no. 14*).

mud-crack structures in mud, though they are preserved in hard rocks at the present time. But Salisbury assigns the columnar structure in clay to concretionary action.

The nature of the cracks and blocks is similar to the polygonal cracks and blocks, with the exception that the cracks extend deeper and change the blocks into columns. The limestone columns in eastern Quebec are reported by Kindle to be from 10 to 24 inches high, and not regular in the number and width of the sides, the number of the sides being commonly five to seven. In Dunn County the columns are hexagonal and of the dimensions mentioned above.

The second type of the columnar mud-crack structure differs from the above mentioned type in that the structure is formed after the sediments have consolidated into hard rocks. It is chiefly due to weathering and thus sometimes called weather-crack structure³⁷. The polygonal cracks which occur in hard rocks under the influence of the sun's heat or frost action may continue to such depths as to form columns. Sosman suggests that this type of structure is caused by internal expansion and made an experiment using cement briquettes to produce the structure. The results show both columnar and polygonal blocks in one cement briquette (fig. 19). This indicates that the polygonal structure and columnar structure are closely related and cannot be definitely separated.

The columns vary in number and width of the sides,

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³⁷ Sosman, R.B., Types of prismatic structure in igneous rocks; Jour. Geol., vol. 24, 1916, pp 230-231.

and are likely to be shorter than those formed in soft deposits, for the penetration of the cracking is much slower in hard rocks than in soft ones. The attitude of the cracks and the form of the columns seem to be best regular than in the first type.

The third type occurs where the columnar mud-crack structure is produced in hard rocks during cooling, subsequent to intense heating by igneous intrusion. The structure is often found in sedimentary rocks which occur in contact with igneous rocks, though the igneous intruded rocks may have the same structure. The rocks have been heated and caused to expand under the influence of the intrusive and have subsequently cracked on loss of heat. The cracking sometimes tends to form a pattern cutting the rock mass into columns. This type of structure was found by Beadnell at Bir Shalatein in Egypt, where, throughout its exposure, the Nubian sandstone exhibits an extremely well developed columnar structure (fig. 20), the individual columns being four, five and six-sided and from two to five centimeters in diameter. The bundles of columns are not parallel throughout the area. At some points they are disposed horizontally, at others vertically, and in places they are curved and pass gradually from the vertical to the horizontal position. In association with the sandstone occur intrusive sheets of basalt and dolerite, by which the former has been metamorphosed into quartzite at some localities. So it may be suggested that the structure has been developed during cooling, subsequent to intense heating of the sandstone by the doleritic intrusion, though no sill is actually visible in contact with the columnar sandstone. Other examples of columnar structure in Nubian

sandstone are known at several localities in the Sudan³⁸.

The fourth type is always found in igneous rocks and it may seem strange to correlate this with mud-crack structure. But as similar structures occur in soft deposits, in hard rocks, sedimentary or igneous, and in igneous rocks, there seems good reason for collecting them into one group of structure, though the causes are quite different.

The columnar structure in igneous rocks is either due to thermal contraction in the crystallized rock or due to convective circulation of the magma while still liquid³⁹. During further cooling after the magma has solidified into rock the cracking is produced by the shrinkage of the mass⁴⁰, the resulting cracks tending to separate the surface into equal areas, i.e., triangles, squares or hexagons⁴¹, and then to extend down to cut the rock mass into columns.

The attitude, size, shape and regularity of the columns depend upon the viscosity, the temperature, the rate of cooling, the regularity of cooling, and the homogeneity of the igneous mass⁴². The columns formed by convection are often vertical or nearly so and wide in proportion to their length; those at Murols described by Dauzère are 1.5 to 2 meters wide and 5 to 10 meters high;

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- ³⁸ Beadnell, H.J.L., Columnar structure in the Nubian sandstone; Geol. Mag., vol. 63, 1926, pp 271-272.
  - ³⁹ Sosman, R.B., op. cit., pp 231-233.
  - ⁴⁰ Iddings, J.P., The columnar structure in the igneous rock on Orange Mountain, New Jersey; Am. Jour. Sci., 3rd ser., vol. 31, 1886, p 324.
  - ⁴¹ Mallet, R., On the origin and mechanism of production of the prismatic (or columnar) structure of basalt; Phil. Mag., 4th ser. vol. 50, 1875, pp 125-130.
  - ⁴² James, A.V.G., Factors producing columnar structure in lavas and its occurrence near Melbourne, Australia; Jour. Geol., vol. 28, 1920, p 458.

those measured by O'Reilly in the Giant's Causway are 0.4 to 0.5 meters in width, varying from 3 to 25 meters in total height⁴³ (fig. 21). Scrope describes columns near La Queuille not less than 15 feet in diameter, and about 30 feet in height⁴⁴. The columns are often hexagonal and may be nine⁴⁵, seven or five-sided, but three and four-sided figures are very rare. The angles of the columns often approximate 120° . On the other hand, columns formed by contraction are usually perpendicular to the cooling surface, but irregular conditions of cooling may cause them to curve in a great variety of ways. They are commonly very long and narrow, usually about 0.2 meters or less in diameter and 20 meters long or over 40 meters in total length. In contraction columns pentagons are likely to be the prevailing type, and four-sided figures are fairly numerous, while hexagons become less important⁴⁶. This type of structure appears to be most frequent in basalt, but it also occurs in other igneous rocks, such as dolerite, trachyte, phonolite, obsidian, etc.

The fifth type of the columnar structure is the stylolitic structure or stylolites. It may seem even stranger to include this with columnar mud-crack structures than to include columnar igneous structures in this class, but again a consideration of the similarity of stylolites to the columns formed in muds justifies the classification here adopted on the basis of form. Furthermore, Hopkins states that the stylolites have been

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⁴³ Cited by Sosman.

⁴⁴ Scrope, G.P., *The geology and extinct volcanoes of Central France*, 2nd. ed., London, 1858, p 136.

⁴⁵ Dana, J.D., *Manual of Geology*, 4th ed., N.Y. 1895, p 261.

⁴⁶ Sosman, R.B., *op.cit.*, pp 224-226.

caused by different agencies; some may be mud cracks, some may be due to the action of rain or spray on the exposed surface and some may be caused by the escape of gases from the limestone mud.⁴⁷

The stylolites often occur along bedding or lamination planes of rocks, resulting in an intricate interteething of the rock by the alternating downward and upward projection of the columns of one layer into the other (figs. 22 and 23). The columns range in length from a fraction of an inch up to 13 inches, the average length being about 3 to 5 inches⁴⁸. In the Tennessee marble the columns vary in length from a small fraction of an inch to 4 inches or more with the diameter of 2 inches or more⁴⁹. In the Breckenridge District, Colorado, the stylolitic columns in quartzite are rarely over one and three-quarters inches in length, the majority being less than one inch⁵⁰. In general the width of the columns is as variable as the length. As a rule the union of the stone at a stylolite parting is so intricate and firm that the rock will break more readily elsewhere than along the suture. A column is usually straight and vertical, but may be curved. Stylolites are always characterized by two principal features: namely, (1) an ever present clay cap at the end, and (2) parallel fluting or striations on the sides⁵¹. The clay cap is usually thin. However, it varies in thickness with the length of the stylolite and the composition of the rock and

⁴⁷ Hopkins, T.C., Stylolites; Am. Jour. Sci. 4th ser. vol. 4, 1897, pp 142-144.

⁴⁸ Twenhofel, W.H., op.cit. pp 518-519.

⁴⁹ Gordon, C.H. On the nature and origin of stylolitic structure in Tennessee marble: Jour. Geol., vol. 26, 1918, p 563.

⁵⁰ Tarr, W.A. Stylolites in quartzite: Science. new series, vol. 43, 1916, pp 819-820.

⁵¹ Stockdale, P.B. Stylolites: their nature and origin, Indiana Univ. Studies, Study no. 55, 1922, p 10.

may attain a thickness of half an inch or more. But in stylolitic structures in quartzite the clay cap was not found. The striations often resemble the slickensides of fault planes and are parallel with the direction of the penetration of the stylolites. The stylolite plane is usually nearly horizontal, but may be inclined. The stylolite columns are commonly at right angles to the bedding planes of the rocks, but some stylolites are found along the inclined bedding planes, with their direction of penetration vertical, instead of at right angles to the stratification. This structure is best developed in limestone, dolomite and marble, but is also present in quartzite and shale.

Spheroidal mud-crack structure.

The term, spheroidal mud-crack structure, is used in this paper to include all the varieties of the mud-crack structure which have curved or irregular joints, and blocks rounded or boulder-like, such as curvilinear structure, cup-and-ball structure concentric structure, exfoliation cracks, spheroidal structure, etc. Though the ^{final shapes of the} resulting blocks in these and the above mentioned mud-crack structure are quite different, yet at the beginning of the formation the blocks bear a close resemblance to those in a mud-crack structure, and may even result from them in various ways. Under favorable conditions the rock mass may be cut at the surface by polygonal cracks. In Peru, Colorado and Pennsylvania this phenomenon was found. If the cracks tend to proceed laterally instead of downward or inward owing to a hydrated condition (figs. 24 and 25), the spalling off of outer layers takes place and will result in the production of a curved or rounded

outline in the solid rock. This change proceeds from the exterior of the rock inward and is mainly due to weathering agencies, and the resulting structure may be called external spheroidal structure. The incipient polygonal cracks may reach several inches in breadth⁵² (fig. 25), and the resulting blocks range from several inches in diameter to the size of very large boulders. The spheroidal structure may be formed during contraction of a cooling igneous mass. Where heat was lost with tolerable uniformity throughout any part of the mass, the spheroidal structure would be formed, where it was lost from a more or less plane surface, but from certain points on it more than others, cup-and-ball structure and curvitarbular structure would be formed⁵³. This phenomenon is accomplished in the inner part of the rock mass and independent of weathering processes, and the resulting structure may be called internal spheroidal structure. In curvitarbular structure the blocks may be about 2 to 4 feet in length and 4 to 12 inches in thickness. The blocks cut by cross-jointing or cup-and-ball structure are commonly from 3 to 6 feet thick, but may reach 15 to 20 feet in thickness. The spheroids vary in size from several inches in diameter to dimensions of large boulders. Between these two types of spheroidal structure lies a third type which may be explained as a concentric structure resulting from the contact of a sedimentary

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⁵² Blackwelder, E., Exfoliation as a phase of rock weathering; Jour. Geol., vol. 33, 1925, pp 793-806.

⁵³ Bonney, T. G., op. cit., pp 146-152.

rock with an igneous intrusion. This was found in the Cobalt district of Ontario, where the slates in contact with gabbro show concentric structure (fig. 26). These slates have been heated and caused to expand under the influence of the intrusive and have subsequently cracked during cooling⁵⁴.

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⁵⁴ Leith, C.K., op.cit., p 49.

Petrographic occurrence of the mud-crack structure.

Used in its narrow sense, the term mud-crack structure is confined to structures in soft deposits, and needs no special statement on petrographic occurrence. But, as used here, the term includes structures occurring not only in soft deposits and in consolidated sediments but also in many other kinds of rocks. In fact, a comprehensive study of mud-crack structures which includes the analogous and related structures shows that most of the main group of rocks contain a trace of mud-crack structure.

Mud-crack structure in sedimentary rocks (or deposits):

Mud-crack structure in mud and clay. Three types of structure are known to occur in mud and clay, namely, parallel, polygonal and columnar structure. The parallel structure was obtained experimentally but not found in natural deposits. It is stated to be due to differential desiccation of the mud. The polygonal structure is well developed in mud. The composition and character of the mud affect the attitude of the structure. The presence of marly material or the addition of sand gives polygons which are much smaller than those formed in clay mud, and a sufficient excess of sand entirely prevents the formation of mud cracks¹. A tenaceous mud may result in the formation

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¹ Kindle, E.M., Some factors affecting the development of mud cracks; Jour. Geol., vol. 25, 1917, pp 137-139.

of larger polygons² with the margins turning up. In the vicinity of Menomonee, Dunn County, Wisconsin, a greenish clay of about five feet in thickness contains columnar structure. But Salisbury attributes this structure to concretionary action³.

Mud-crack structure in shale. Both polygonal structure and columnar structure may be found in shale, and spheroidal structure is also reported to occur in it. In the Mauch Chunk shales of Pennsylvania a polygonal mud-crack structure was observed by Barrell. Where the surfaces of the mud-cracked shale laminae are well preserved, they are frequently seen to be plate-like polygons with raised rims, giving surfaces concave upward. The depth of the cracks appears to be limited by the thickness of the stratum, being not more than 0.5 to 1.0 inch⁴ (fig. 27). The fossil sun-cracks in the Shinarump shale may be cited here as an example of the columnar mud-crack structure in shale⁵ (fig. 9). The stylolitic structure is stated by Dr. Twenhofel to be occasionally present in shale⁶. In County Cork, Ireland, a spheroidal structure was found in a shale, which, instead of splitting into the laminae of deposition, has separated into spheroids decomposing in concentric shells, and each of

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² Doerr, J.E., Investigation of the character of mud-cracks; Thesis, Univ. of Wis., 1924.

³ Salisbury, R.D., Columnar structure in subaqueous clay; Science, vol. 5, 1885, p. 287.

⁴ Barrell, J., Origin and significance of the Mauch Chunk Shale: Bull. Geol. Soc. Am., vol. 18, 1907, pp. 457-458.

⁵ Gilbert, G.K., Geology of the Henry Mountains, U.S. Geog. G.S. Rocky Mountain Region, 1880, p. 9.

⁶ Twenhofel, W.H., Treatise on Sedimentation; 1st, ed., Baltimore, 1926, p. 518.

which encloses a smaller spheroid⁷. On the Fiveshire coast, near Elie, an ellipsoidal modification of the spheroidal structure was observed by Bonney in a lenticular fragment of shale⁸.

Mud-crack structure in sandstone. Parallel structure, polygonal structure and columnar structure have been found in sandstone. Parallel structure is represented by the sheet structure which often occurs in sandstone quarries, especially on weathered surfaces. The quarries in the Baraboo region, Wisconsin, furnish good examples of this. Polygonal structure in sandstone includes both secondary and fossil mud cracks. The fossil polygonal structure occurs in the sandstone at Tunnel City, Wisconsin, where the sandstone is gray to yellowish-gray and fine-grained. The polygons range from a fraction of an inch to about 6 inches in diameter. The polygonal structure formed by the sun's heat was found in the desert of Tumbez, north-west Peru⁹, where the structure occurs on sandstone pebbles. The size of the polygons is, of course, restricted by the size of the pebbles. The columnar structure in sandstone is reported by Beadnell to occur at Bir Shalatein, about 90 kilometers south of Berenice, Egypt, where the rock composing the hillock is the brown-weathering current bedded Nubian sandstone, in which exists an extremely well-developed columnar¹⁰.

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⁷ Jukes, J.B., The school manual of geology; 5th. ed., Edinburgh, 1863, pp 136-137.

⁸ Bonney, T.G., On columnar, fissile, and spheroidal structure; Quart. Jour. Geol. Soc. London, vol. 32, 1876, p 149.

⁹ Brown, C.B., On some effects of wind and sun in the desert of Tumbez, north-west Peru; Geol. Mag. vol. 61, 1924, pp 337-339.

¹⁰ Beadnell, H.J.L., Columnar structure in the Nubian sandstone; Geol. Mag., vol. 63, 1926, pp 271-272.

structure. The columns are usually not as large as in igneous rocks.

Mud-crack structure in limestone and dolomite. Some limestones have polygonal and columnar structures, including stylolites. The Stylolites are also known to be present in dolomite.

Polygonal mud cracks occur in a yellowish-gray limestone near the base of Foraker limestone in Kansas, where the polygons range from half an inch to about 2 inches in diameter. In a bed of limestone at the base of Mount Wissick on the shore of Temiscouta lake opposite Cabano, Quebec, columnar structure was observed by Kindle. The limestone is a dark, blue, hard, fine-textured rock.¹¹ Two types of structure occurring in this limestone are suggested to be fossil mud cracks.

The stylolitic structure is well developed in limestone and dolomite. Many examples can be obtained from the literature on this subject. The Indiana limestones offer examples of the largest and best developed stylolites in America, and the Muschelkalk of Germany presents the most complex stylolitic structure known.

Mud-crack structure in metamorphic rocks.

Mud-crack structure in slate. The ordinary mud-crack structure is likely to be rare in slate, but the spheroidal structure occurs in slates having concentric cracks caused by igneous intrusives. The slates in contact with their contact with the gabbro in the Cobalt district of Ontario

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¹¹ Kindle, E.M., Columnar structure in limestone; Can. Geol. Sur., Mus. Bull. no 2, Geol. Ser, no. 14, 1914, pp 1-5.

may be cited as an example.

Mud-crack structure in quartzite. Stylolitic structure is reported by Tarr to occur in quartzite in the Breckenridge District, Colorado, where the stylolites consist of small columns, with etched surfaces¹². Quartzite boulders formed by spheroidal cracks were found by Blackwelder in Medicine Bow Mountains, Wyoming, the cracking being due to the heat of a forest fire¹³.

Mud-crack structure in marble. Stylolitic structure is sometimes found in marble. In the East Tennessee Valley this structure was found by Gordon in the Tennessee marble which is subcrystalline to crystalline in texture and varies in color from light pink and gray to differing shades of red, dark chocolate and cedar¹⁴.

Mud-crack structure in Igneous rocks.

Mud-crack structure in granite. Sheet structure, exfoliation cracks and concentric structures are often found in granite and tabular structure is occasionally observed in it.

The best examples of sheet structure in granite may be obtained from the granite quarries in Vermont, New Hampshire, Maine, Massachusetts, Connecticut and Rhode Island.

¹² Tarr, W.A., Stylolites in quartzite; Science, new ser., vol. 43, 1916, pp 819-820.

¹³ Blackwelder, E., Exfoliation as a phase of rock weathering; Jour. Geol. vol., 33, 1925, p 796.

¹⁴ Gordon, C.H., On the nature and origin of the stylolitic structure in Tennessee marble; Jour. Geol., vol. 26, 1918 pp. 561-568.

Granite boulders with exfoliation cracks were seen in Owen Valley, California, by Blackwelder¹⁵, where the relation between the polygonal cracks and exfoliation boulders was clearly shown. Concentric structure in granite is mentioned by Shaler, who found examples at Cape Ann, near Rockport and in other regions¹⁶. The homogeneity of granite is likely to be favorable for the above mentioned structures.

Bonney mentions that tabular structure may be seen in many granites, as, for example, at Pardenick Point, near the Land's End¹⁷.

Mud-crack structure in trachyte, phonolite and obsidian. Columnar and spheroidal structure may be found in these rocks. Bonney¹⁸ states that columnar structure was observed in trachyte at Pic de Sancy, near Cascade of the Dore, where the columns are curved, and in the district of Mont Dor, Anvergue. Columnar structure occurs in the phonolite on the island of Fernando de Noronha¹⁹. Both the columnar and spheroidal structure are known to be present in obsidian; the well developed columns of Obsidian Cliff in the Yellowstone Park are the best example of the columnar structure in obsidian. The columns are 50 to 60 feet high²⁰. Spheroidal structure in

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¹⁵ Blackwelder, E., op.cit., pp 804-805.

¹⁶ Shaler, N.S., Notes on the concentric structure of granite rocks: Proc. Boston Soc. Nat. Hist., vol. 12, 1868-1869, pp 289-293.

¹⁷ Bonney, T.G., op.cit., p 145.

¹⁸ Bonney, T.G., op.cit., pp 141-142.

¹⁹ Dana, J.D., Manual of Geology; 4th. ed., N.Y. 1895, p 263.

²⁰ Dana, J.D., op.cit., pp. 263-264.

obsidian is reported by Bonney.

Mud-crack structure in andesite. Parallel mud-cracks structure and concentric structure have been known to occur in andesite. In the desert of Tumbez, north-west Peru, the parallel cracks were found by Brown to be present on some andesite pebbles²¹ (fig.2). Concentric structure sometimes occurs in andesite, where the rock tends to spall off at the surface²². These types of structure are chiefly due to weathering agencies especially sun-heat.

Mud-crack structure in diabase, dolerite and gabbro. Polygonal, columnar and spheroidal structures are reported to be present in diabase. In Montgomery County, Pennsylvania, the surface of the great diabase sill shows at several localities a network of cracks which cut the rock mass into polygons. The surface of diabase boulders also shows polygonal structure. The former is regarded as produced by shrinkage on rapid cooling of rock mass and the latter by expansion of the surface layers during the exfoliation of the boulders under the action of frost²³. At other localities in southern Pennsylvania the same phenomenon has also been found. At Orange Mountain, New Jersey, columnar structure is well developed in the diabase or dolerite which forms a lava sheet²⁴. At many localities in California concentric structure has been found to occur on diabase boulders. The

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²¹ Brown, C.B., op.cit., p 339.

²² Leith, C.K., Structural Geology, revised ed., N.Y., 1923, p 57.

²³ Wherry, E.T., Apparent sun-crack structures and ringing-rock phenomena in the Triassic diabase of eastern Pennsylvania: Proc. Acad. Nat. Sci., Phila., vol. 64, 1912, pp 169-172.

²⁴ Iddings, J.P., The columnar structure in the igneous rock on Orange Mountain, New Jersey: Am. Jour. Sci. 3rd ser., vol 31, 1886 pp 321-331.

concentric cracks are suggested by Balckwelder to have been produced by the expansion of the outer hydrated portion of the rock.²⁵ Tabular structure was found, by Bonney, to occur in dolerite in an intrusive mass under the Castle, Burntisland, and in the gabbro of the Gimlet rock, Pwehelli, and of the Cuchullin Hills²⁶.

Mud-crack structure in basalt. Basaltic rocks are much more generally columnar than other kinds of igneous rocks and thus well known for columnar structure, On this account the structure is often called basaltic parting, basaltic columns, etc. The rapid cooling of the basaltic lava at the surface may be the reason for the well developed columnar structure in this kind of igneous rock. One of the most noted localities illustrating columnar structure is the Giant's Causeway on the northern coast of Ireland. Others are found on the Isle of Cyclops on the coast of Sicily, in the Sydenham area, northeast of Melbourne, Australia, and in Central France.

Mud-crack structure in pyroclastic rocks. Columnar structure is known to occur in the volcanic mud which lies beneath a bed of basalt in Tideswell Dale, Derbyshire; and in a palagonite tuff in Iceland, where the structure is imperfect. A very fine spheroidal structure may be seen in a volcanic ash near Sant Lucia, Italian Tyrol, and in the agglomeratic ash of the Binns, Burntisland, where the structure is wholly independent of the form of rock and sometimes occurs where a distinct stratification may be observed, through the planes which it cuts²⁷.

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²⁵ Blackwelder, E., op.cit., pp793-806.

²⁶ Bonney, T.G., op.cit., p 145.

²⁷ Bonney, T.G., op.cit., p 141.

Mud-crack structure in iron ore, quartz vein,
coal and salts, and in ice.

Columnar structure was observed by Bonney²⁸ in hematite ore from Yorkshire, where the columns are about $1/8$ inch in diameter; in a large quartz vein at Svolvær, Lofoten Island; and in coal in contact with basalt from Ayrshire and Yorkshire, where the structure may be due to cooling subsequent to the heating of the coal by the basalt. In the Takla-Makan desert of Central Asia polygonal structure was found by Huntington²⁹ in salt. After the salt became dry it broke up into pentagons from 5 to 12 feet in diameter. The columnar structure in ice is described by Bonney³⁰ as follows: ice, when kept for some time very near a temperature of 32°F. often exhibits a beautifully regular columnar structure. Ice crystal impressions which resemble mud cracks are not uncommonly observed. These can only be attributed to a contraction of the mass. The pattern of the structure in ice is smaller than that in rocks.

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²⁸ Bonney, T.G., op.cit., p 141.

²⁹ Huntington, E., Pulse of Asia, 1907, Chapter 12 and pp 251-252 (cited by Twenhofel).

³⁰ Bonney, T.G., op.cit., p 141.

Climatic conditions and topographic features as factors controlling the formation of the mud-crack structure.

If only the cracks which occur in mud or soft deposits be taken into consideration, the main climatic and topographic factors involved are those which favor the preservation of the mud in which the cracks occur and the activity of the agencies by which the mud can be dried and cracked. But in studying the mud-crack structure comprehensively, it is necessary to consider many formative processes; some of these have an intimate relation to climate and topography, while others are independent of them.

However, we are here concerned only with the processes which are mainly dependent on climate and topography, namely, insolation, congelation or frost action, and hydration. The influence of climate and topography on these processes is studied by observing the present development of jointing in muds and hard rocks.

For the sake of clearness, the effects of climate and topography will be discussed separately, although these two factors are commonly so closely related that this procedure involves some repetition.

Climatic conditions and the formation of the mud-crack structure.

As insolation and congelation are chiefly responsible for the formation of mud-crack structures, the tropical, temperate arid and frigid climates are likely to be the most important.

It seems convenient here to adopt a combination of the climatic classifications used by Professors Twenhofel¹, Grabau², and Barrell,³ whereby the individual climatic conditions are classed as frigid, temperate rainy, tropical rainy, temperate semi-arid, temperate arid and torrid arid.

Frigid climate. In regions with a frigid climate the ground is frozen most of the time and usually covered with snow and ice. The sediments are mostly of mechanical origin. Fine silt deposits are uncommon, and insolation is not effective. Perfect cracks formed in mud by insolation are very rare or even absent, due to their destruction by freezing. But there is a deep penetration by frost action which may produce frost cracks on a scale that is commonly larger than that of the other types of the mud-crack structure.

Temperate rainy climate. In regions with this climate the vegetation is luxuriant, decomposition becomes dominant, and the deposits may contain fine silts and muds. But commonly the substratum is permanently soaked with water, so that there is rarely any desiccation for producing mud cracks in the soft deposits, though the activity of insolation is greater than in a frigid climate. Frost action may be the most important agency producing cracks in hard rocks. In the cold temperate regions there is a long season of alternate freezing and thawing, the

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¹ Twenhofel, W.H., Treatise on Sedimentation, 1st. ed., Baltimore, 1926, pp 96-109.

² Grabau, A.W., Principles of Stratigraphy, 2nd, ed., N.Y. 1924, pp 74-78.

³ Barrell, J., Relations between climate and terrestrial deposits: Jour. Geol. vol. 16, 1908, pp 159-190, 255-295.

effect of which is very great. And, the more plentiful the moisture, the more prevalent is the frost and thus the more intense the frost action. On the elevated land, where the rock surface is mostly exposed, the effect of frost action may be conspicuous, and many types of mud-crack structure due to this action may be found. The variations of temperature due to insolation and radiation can also promote frost action, though insolation itself is likely to be unable to do much mud-cracking. Hydration seems to be very active and may be responsible for some types of exfoliation crack structure⁴.

Tropical rainy climate. Most tropical areas may have either nearly constantly rainy climates or intermittently rainy climates. The latter seem to be prevalent. As, in regions with the climate, decomposition is dominant and vegetation may be luxuriant, especially under a constantly rainy condition, the silts and muds produced are very abundant and spread over comparatively low lands. Insolation is more active and thus desiccation of the muds may take place. With an intermittently rainy condition most of the fine deposits dry out during the periods of drought with consequent mud-cracking. But this feature may not be preserved as wetting tends to destroy it, and, even where preserved, the cracks seem to be not extensive. Frost action is practically absent in the lowlands of the tropical regions⁵ and insignificant in the elevated parts, so that the mud-crack structure which is due to frost action is very rare. In

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⁴ Blackwelder, E., Exfoliation as a phase of rock weathering; Jour. Geol., vol. 33, 1925, pp 801-806.

⁵ Scott, W.B., An introduction to Geology, 2nd, ed., N.Y., 1916, pp 113-114.

constantly rainy regions the high humidity and the heavy vegetation weaken and prevent the action of the sun⁶, so that the mud-crack structure in hard rocks may not be well developed. But in intermittently rainy places during dry periods insolation may affect the exposed rock masses, resulting in the formation of some types of exfoliation-crack structure. Hydration is also active in these climates and may cause the development of exfoliation-crack structures.

Temperate semi-arid climate. In the regions of this climate there is not sufficient moisture to support a complete vegetable cover over the surface, as rain falls only during certain periods of the year, and the sediments are carried and dropped to form flood plains and alluvial fans. The sediments contain a considerable amount of silts and muds, and become thoroughly mud-cracks during the seasons of drought. The mud cracks thus formed are likely to be the most developed and significant. On account of the scarceness of vegetation and dominance of disintegration the exposed rock surfaces may be ^{of} considerable area, so that ample opportunity is given to weathering agencies for developing some types of mud-crack structure. Owing to the low humidity insolation is very effective and radiation is also rapid at night. As there are very rapid changes to temperature, exfoliation is very dominant and accordingly concentric structure and probably sheet structure may be well developed. Frost action is known to be important in cold temperate regions. During the rainy season the effect of the alternation

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⁶ Van Hise, C.R., A Treatise on Metamorphism; Mon. 47, U.S.G.S., 1904, p 438.

of freezing and thawing may be great and may result in the formation of some types of the mud-crack structure in hard rocks. In short, in the regions of the temperate semi-arid climates insolation is more active during dry seasons, while congelation is more effective during the rainy or moist seasons.

Temperate arid climate. In the regions of this climate rainfall is rare, decomposition is very slight, and vegetation is extremely sparse. The sediments are the result of rock disintegration and abrasion and thus contain chiefly coarse particles and very small amounts of silts and muds. However, the torrential rainfall of such climates may form temporary lakes containing deposits of silts and muds. When the lakes dry up, the deposits become mud-cracked, and prolonged drying may cause well developed cracks which will be well preserved owing to the long periods between consecutive rainfalls. The rock masses are mostly bare, especially in mountainous parts. On account of the extremely low humidity insolation is very intense, and the diurnal, cyclonic and seasonal changes of temperature result in the formation of concentric and sheet structures of various dimensions. Frost action is not so effective as in temperate semi-arid climates, due to deficiency of moisture.

Torrid arid climate. In the regions with this climate disintegration is much more important than decomposition and vegetation is extremely sparse. The sediments consist of coarse particles, sand being the common and mud very rare. Most of the rock surfaces are exposed. This may be partly due to the sparseness of vegetable cover and partly due to the intensity of the wind action. Well-developed mud cracks are uncommon

in such regions. Frost action is practically absent. Insolation is very intense. The annual changes of temperature in the torrid regions are about 10° to 20° C.⁷ and the effect is a minimum as compared with temperate and Arctic regions. But the diurnal changes of temperature are very great. According to Branner⁸, in Brazil the diurnal change of temperature from the minimum at night to the maximum in the sun frequently ranges from 47° to 107° F., the average being about 90° F. In some desert regions the diurnal changes may be still greater. These great diurnal changes of temperature alone may result in the development of conspicuous concentric structure, sheet structure, and polygonal structure, though the dimensions of the structure may be great or small. In addition the cyclonic and seasonal changes of temperature promote the formation of mud-crack structure.

Topographic features and the formation of the mud-crack structure.

For the formation of mud cracks the favorable topographic features are the comparatively low lands, or, more specifically, according to Barrell⁹, the playas, the marginal belt of the interior lakes, the river flood plains and the littoral zone. But, if, in addition, the analogous and related structures in hard rocks are taken into account, the problem becomes a little complicated, and most of the topographic features should be consid-

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⁷ Van Hise, C.R., op.cit., p437.

⁸ Banner, J.C., Decomposition of rocks in Brazil: Bull. Geol. Soc. Am., vol. 7, 1896, pp. 285-286.

⁹ Barrell, J., Relative geological importance of continental, littoral and marine sedimentation; Jour. Geol., vol. 14, 1906, pp 524-568.

ered, though some may bear but little relation to the formation of the mud-crack structure. Following Dr. Twenhofel's classification of topography, the relation of the topographic features to the formation of the mud-crack structure will be stated as follows.

High youthful topography. In the regions of high youthful topography the precipitation may be partly rain and partly snow. If the higher levels are covered by snow, frost action may be prevented¹⁰ and not effective. If the higher levels are free from snow, frost action is very intense and tends to cause some types of structure, such as polygonal structure and exfoliation-crack structure, except in the regions in the torrid zone. The effect is especially strong on cliffs and mountain sides¹¹. Insolation becomes more important in elevated and steep mountains, especially in the higher portions of the temperate zones, where the steep rock faces favor perpendicular action by the sun. The heat gained in the day is rapidly radiated at night. These large changes of temperature may result in the development of various types of insolation-crack structure. The rock surfaces are constantly exposed to the work of frost and the sun. As the sediments are the result of disintegration, they contain little mud and do not favor the formation of mud cracks. However, if the load of the streams is large, large alluvial fans may be formed where the streams leave the highland, and mud cracks may be found on such deposits.

Mature and low youthful topography. In the regions

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¹⁰ Barrell, J., op.cit., Jour. Geol., vol. 16, 1908, p 172.

¹¹ Van Hise, C.R., op.cit., p 442.

of this topography the sediments are both coarse and fine and the rock surfaces are both exposed and covered. Under conditions of sufficient rainfall vegetation is heavy and decomposition becomes dominant. Thus the sediments contain chiefly sands, silts and muds and are carried to the place of relative permanent deposition. Under conditions of intermittent rainfall decomposition remains dominant, and part of the sediments are composed of silts and muds and deposited on the flood plains. Under conditions of slight rainfall disintegration dominates over decomposition with the result that the sediments consist mostly of coarse materials. However, very fine silts are deposited in ephemeral lakes. Mud cracks are likely to be uncommon in the first case owing to the high humidity but are well developed on the flood plains and deltas in the second case and on the bottom of playa lakes in the third case. The rock surfaces are largely exposed in slightly rainy regions, partly exposed in intermittently rainy regions and mostly covered in sufficiently rainy regions. The effect of both insolation and congelation varies with the elevation; the greater the elevation the more the insulating and congelating effect. But, insolation is likely to be more effective in slightly rainy regions, while the congelation is likely to be more active in sufficiently rainy regions. The formation of the mud-crack structure is thus controlled.

Topography of old age. The old topographic regions may be arid or humid. In both cases the land surfaces are mostly mantled either with vegetation or with wind deposits.

The rock masses which are responsible for the formation of the cracks in hard rocks and the fine deposits which favor the devel-

opment of mud-cracks are not freely exposed to the action of frost and sun, though insolation and congelation may be effective in some places. But in such regions the most favorable places for the formation of mud cracks have been found to be the marginal belts of interior lakes. The water level of such lakes varies with the rainfall and discharge; when the rainfall is slight or the discharge is great, the surface of the lake contracts and thus the areas which cover the margin with fine deposits are left to be exposed to the air and sun, so that mud cracks may be well developed on these marginal areas.

Shore line topography. Near the shore the sediments are composed mainly of fine materials, though beach gravels may be abundant at some localities. The hard rock surfaces are not prevalent, unless a youthful shore is present. Insolation and frost action are likely to reach their minimum effectiveness. Hence, conspicuous and well developed mud-crack structure in hard rocks is not common in the littoral regions. The mud cracks, however, are best developed and most wide-spread in the littoral zone. This zone forms a narrow belt between the average highest and lowest tides of the month. The mud cracks are usually confined to an upper faction of the littoral zone. The climate, the texture of the mud and the wind action of the region as well as the insolation in it control the development of the mud cracks. A broad development appears to occur in arid regions where continental river deposits have been previously built. In this case the mud cracked sediments are frequently saliferous.

Processes and causes of the mud-crack structure.

As the term mud-crack structure as used in this paper includes many types of structures, it is necessary to consider many processes of forming this structure. One individual structure may have its own peculiar cause, another may be due to several causes, and some are of doubtful origin. In order to sum up the origins of the structure as simply as possible, only the principal and prevailing causes are taken into consideration. These may be stated as desiccation, insolation, congelation, contraction, convection, hydration and others. In regard to the stresses they are either tensional or compressional, the former being responsible for the most important types of the mud-crack structure.

Desiccation. The term, desiccation is here used to imply the elimination of water and the coherence of particles in soft materials which results in shrinkage. It is responsible especially for mud cracks. The process is aided by insolation and wind action, which promote evaporation, and is governed by the nature of the mud, the thoroughness of its saturation, and the temperature and dryness of the air. Of course, the more intense the insolation and wind action, the more rapid is the desiccation. Tenacity in the mud may cause slow desiccation and salinity may stop it entirely¹. Where the ground remains permanently soaked with water desiccation does not

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¹ Doerr, J.E., Investigation of the character of mud cracks; Thesis, Univ. of Wis., 1924.

come into existence, while high temperature and dryness of the atmosphere greatly favor desiccation. The rate of desiccation affects the attitude and dimensions of the mud cracks and blocks, and is thus of influence on the type of structure formed. The nature of this relation has been mentioned in the foregoing chapters.

The stresses acting in this process are tensional, forming joints normal to the direction of the stress. Horizontality of the stress is shown by the verticality of the plain of mud cracks. The weak parts in the mud are especially susceptible to rupture, so that the mud with its lowest tensile strength breaks most easily by tension.

Insolation. As usually defined, insolation is the action of the sun in producing changes in the temperatures of substances, especially rocks. The intensity of the sun's rays and radiation, appear to be the main factors involved. Heating by insolation in general causes expansion of rock masses, while cooling by radiation causes contraction. The heat conductivity of the rocks also plays a part, but usually a small one. The alternation of heating and cooling will result in rapid changes in volume and thus destruction of rock masses. Many types of the mud-crack structure are caused by insolation. The parallel mud-crack structure due to insolation is occasionally found and the polygonal structure is not uncommon. As in hard rocks, the fracturing or cracking due to insolation often tends to extend roughly parallel to the rock surface² rather than nearly at

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² Van Hise, C.R., A Treatise on metamorphism: Mon. 47, U.S.G.S., 1904, p 435.

right angles to it. Well-developed columnar structure by insolation is rare, unless other agencies participate in the action. Insolation is most favorable for concentric or exfoliation-crack structure, and some types of sheet structure are attributed to it. Naked rock surfaces are heated by exposure to the sun and expanded during the day, and radiation causes contraction of the surface at night. The expansion of different rocks per degree centigrade varies from less than 0.000023 cm. to about 0.000046 cm. per meter. If the change of temperature for a given day is supposed to be 40°C and the length of the rock surface to be 1 meter at the mean temperature, then its length at the coolest period will be from 0.99908 to 0.99954 m., and at the hottest period from 1.00046 to 1.00092 m³.

At some distances below the surface the temperature of the rock is assumed to be near the mean; consequently at the coolest part of the day (or at night) the surface of the rock is shorter than the rock below, and at the hottest part of the day it is longer than the rock below. If the elastic limit of the rock be surpassed, during this strain, breaking occurs. Where the breaking is tensional the cracks may be arranged as parallel mud-crack structure, as shown by the cracks on the andesite pebbles in the desert of Tumbes in Peru (fig. 2), or may form a network as polygonal mud-crack structure, as shown by the cracks on the sandstone pebbles in Peru⁴ (figs. 12 and 13). If the cracking extends to a depth greater than

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³ Van Hise, C.R., op.cit., p 434.

⁴ Brown, C.B., On some effects of wind and sun in the desert of Tumbes, north-west Peru: Geol. Mag., vol. 61, 1924, pp 337-339.

the distances between the cracks on the surface, columnar mud-crack structure may result. But this seems to be uncommon, for the cracking often tends to extend laterally during long periods of heating and cooling so that the diameter of the columns is rarely less than their depth. The strain set up by the expansion and contraction also causes shearing roughly parallel to the surface which may result in the development of concentric structure. Furthermore, the expansion seems to produce a tendency for the heated outer parts to separate from the deeper inner parts, and thus some types of sheet structure may result.

The temperature changes are diurnal, cyclonic and seasonal. The rate is far greater for the diurnal and cyclonic than for the seasonal changes, but the amount of the seasonal change is considerably greater than that of the other two⁵. Accordingly the individual structures of small size are mainly due to the diurnal and cyclonic changes in temperature, while those of large dimensions are due to the seasonal changes.

According to Van Hise rocks vary in their power to resist the effect of insolation. Sandstones are refractory, limestones and shales are less so and crystalline rocks are most affected. The explanation given is that where the rock is a solid continuous mass with little or no pore space, the expansion can be taken up only by elasticity, so that where the stresses accumulate beyond the elastic limit, ruptures are produced⁶. This statement is in partial accord with the natural

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⁵ Van Hise, C.R., op.cit., pp 436-437.

⁶ Van Hise, C.R., op.cit., p 439.

occurences which show concentric structure and sheet structure due to insolation most often in granites;but also in sandstone and diabase, and parallel structure and polygonal structure^{in sandstone} and andesite. The effect of insolation varies with latitude and altitude;the greater the altitude and the lower the latitude the more intense the insolation.

Congelation. This term denotes the mechanical action of freezing water on mud or rock masses. Water, on freezing, expands 9 per cent of its volume. This expansion may exert a pressure of somewhat more than 2000 pounds per square inch⁷, and is thus a powerful destructive agency. The alternation of freezing and thawing promotes the action. The agency is effective in both soft deposits and hard rocks, and responsible for several types of the mud-crack structure. The polygonal structure is not uncommon wither in muds or hard rocks; some types of concentric structure are reported to be due to congelation, and this agency in connection with some other agencies may produce columnar structure. No rocks are formed of continuous sheets of material but are rather to be considered as masses of blocks either divided by joints and clefts or traversed by minute crevices, rifts and pores, which often or always take up and retain quantities of water. When exposed to a low temperature, the water freezes, and the resulting expansion moves the rock masses. By the repitition of this process, incipient cracks may become enlarged. The resulting cracks may be irregularly arranged, but where the rock is homogeneous and the pores which contain water are uniform, a polygonal mud-

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⁷ Scott, W.B., An introduction to geology, 2nd. ed., N.Y. 1916, p 113.

crack structure may be formed. This may be because the cracks tend to radiate from the points where the expansion is occurring and to join one another to form a polygonal structure. The best examples are reported to be the polygonal cracks on the surface of the diabase in Montgomery County, eastern Pennsylvania⁸ (figs. 14 and 15), and the polygonal cracks on the surface of the Twentymile sandstone in Routt County, Colorado⁹ (figs. 10 and 11). The diabase and sandstone are homogeneous rocks. If the water distributed within the rock tends, when it freezes, to set up a peripheral stress, a concentric structure may be formed. In connection with other agencies, such as insolation hydration, etc., congelation may cause polygonal structure to be extended to form columnar structure and may widen the concentric cracks. In these cases the effect of congelation varies with the space between the particles of the rocks. If the space is so great that the expansion of freezing need not move the grains, disruption may not take place. If the particles are so close that the rock is kept saturated with water, and cannot easily escape, the effect of congelation is likely to be great.

Frost action may form mud cracks in soft deposits in several ways. It has been observed that severe frosts leave mud flats patterned by cracks which may form a network cutting the mud into polygonal blocks, the structure thus form-

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⁸ Wherry, E.T., Apparent sun-crack structure and ringing-rock phenomena in the Triassic diabase of eastern Pennsylvania: Proc. Acad. Nat. Sci. Phila., vol. 64, 1912, pp 169-172.

⁹ Campbell, M.R., The Twentymile Park District of the Vampa Coal Field, Routt County, Colorado; Bull 748, U.S.G.S., 1923, p 8.

ed being often of large size. The frost cracks in the Canning River Region, northern Alaska, form the best example¹⁰ (fig. 5), and in Iceland the same structure was noticed in superficial deposits. Hawkes ascribes the origin of this phenomenon to contraction produced by hard frost. In addition he states that this action was noted to have occurred after a night temperature of -10°C . The process was studied by freezing a mud layer in a beaker. At a temperature of -15°C a network of fissures was formed. A temperature of -2° to -3° produced no such effect¹¹. Moore, in explaining the origin of the mud cracks formed under water in a small pond in Centre County, Pennsylvania, suggests that the cracks are due to the ground freezing, with expansion, and later thawing, with contraction, beneath the water¹². Still another interesting feature which occurs in frozen mud is stated by Udden. His description is given as follows:

"When mud freezes, the water which it contains has a tendency to crystallize. The crystals begin to grow on the surface, and the continuous coating of ice is apt to form if water is present in sufficient quantity. Such a coating will be much thicker along certain lines where the freezing commenced, and the ice will often extend as a thin plate some distance down in the mass, which is thus fissured by clefts filled with ice crystals. These clefts are mostly straight, and they branch and cluster after the crystalline properties of water, uniting preferably at angles of 60 and 120 degrees. When dry winds cause the crystals to disappear, the empty cracks remain open." ¹³

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- ¹⁰ Leffingwell, E. de K., The Canning River Region, northern Alaska: Prof. Paper 109, U.S.G.S., 1919, pp 205-211.
¹¹ Hawkes, L., Frost action in superficial deposits, Iceland: Geol. Mag., vol. 61, 1924, pp 509-513.
¹² Moore, E.S., Mud cracks open under water: Am. Jour. Sci., 4th ser. vol. 38, 1914, pp 101-102.
¹³ Udden, J.A., Fossil frost cracks: Sci. Am., vol. 72, 1895, p 102.

In his experimental study Doerr found noticeable effects in frozen muds. He states that the freezing of the water in muds causes incipient fractures which later develop into closely-spaced, short, isolated, angular cracks, forming a distinct pseudopolygonal pattern¹⁴. The writer's experiments at low temperatures, also showed some incipient fractures on the frozen mud. They were minute and irregular and remained open after the mud had thoroughly dried. The incipient fractures may be merely due to contraction of the mud by freezing; for it was found experimentally that the whole mass of mud in a small pan showed definite contraction when freezing.

Like insolation, the effect of congelation varies with latitude and altitude. The effect is very great in the cold temperate and frigid regions where there is a long season of alternate freezing and thawing, while it is nil in the lowlands of the tropical zone where the temperature does not fall to 0°C. Where the slopes are sharp and the elevation is great the effect is likely to be great; where the land is low and the topographic variation is slight the effect is likely to be small.

It is noteworthy that, whereas the formation of ice from water involves expansion, the freezing of mud results in contraction. In congelation the stresses are always tensional and the stress acts normal to the plane of the crack which it produces.

Contraction. The following discussion is

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¹⁴ Doerr, J.E., An investigation of the characteristics of mud cracks: Thesis, Univ. of Wis., 1926.

confined to the contraction of rocks due to cooling. All rocks on cooling, tend to contract, but are able to extend somewhat under tension. Where the tension due to contraction on cooling is able to overcome this power of extension the rocks crack. This agency acts not only in igneous rocks but also in the rocks in contact with them. In igneous rocks it is controlled by several factors, namely, the viscosity of the rock, the temperature of the rock, the rate of cooling, the regularity of cooling and the homogeneity of the rock. Anyone of these factors may cause a variation of the attitude, size and shape of the structure. Contraction causes polygonal, columnar and concentric structure, and some horizontal parallel cracks may also be due to this cause. When the mass of molten rock is cooling uniformly from the surface, it will, in consequence of the mathematical principle of least work, crack into polygonal areas on the surface. If the cooling is slow from the surface inward, the normal course of crystallization of the igneous rock consists in the separation of certain portions as crystals while the remainder stays liquid until the lower temperature is reached. Under this condition the cracks may be well developed only in the first solidified portions due to rapid cooling and may not continue to extend into the slowly cooled portions when the rock crystallizes slowly and where the tension may be equal to the extensibility. Thus the polygonal mud-crack structure is formed. The apparent sun-crack structure in the diabase of eastern Pennsylvania¹⁵, may be cited as example of this type (fig. 16): The polygonal structure due to the contraction of igneous rocks is likely to be confined to the surface parts of the in-

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¹⁵ Wherry, E.T., op.cit., pp 169-172.

trusive bodies, such as sills and dikes, which are cooled by the adjacent rock. If the cooling is rapid, the molten mass solidifies rapidly from the surface inward, the cracks extend to a great distance, and a columnar mud-crack structure ^{is formed. The columnar structure} occurring in surface flows is mostly of this type. According to Bonney¹⁶, the relation between the types of concentric structure and the cooling condition is that when heat is lost with tolerable uniformity throughout any part of the rock mass, spheroidal structure may be formed; when it is lost from a more or less plane surface, but from certain points on it more than others, curvilinear structure and cup-and-ball structure may be formed; and when cooling is taking place uniformly from all the points of a plane surface, tabular structure may result. James¹⁷ states that the cross joints are formed after the columns. The vertical columns continue to shrink as they cool. Horizontal contraction simply causes a widening of the vertical joints or cracks, but tension in other directions can only be relieved by cracking. There are centers of contraction distributed equally along each column and the particles will concentrically be drawn toward these points. This causes not only concentric weakenings and cracking but also a well-defined horizontal joint midway between any two centers of contraction. The spheroids in the columns are not found passing from one column to another, but each column is divided into blocks, and each block is composed of concentric spheres separated by a contrac-

¹⁶ Bonney, T.G., on Columnar, fissile and spheroidal structure: Quart. Jour. Geol. Soc. London, vol. 32, 1876, p 152.

¹⁷ James, A.V.G., Factors producing columnar structure in lavas and its occurrence near Melbourne, Australia: Jour. Geol., vol. 28 1920, pp 458-469.

tion crack or line of weakness along which weathering will later act and finally give rise to concentric structure. Some types of sheet structure are supposed to be due to contraction in the cooling of granites still under their loads of beds¹⁸.

The contraction of the sedimentary rocks due to cooling subsequent to their intense heating by igneous intrusion also results in the development of columnar and concentric structure. The rocks are heated under the influence of the intrusives and thus caused to expand and on loss of heat they tend to crack, either forming a network of cracks or concentric cracks. The former is shown by the columnar structure in the Nubian sandstone in Egypt, which occurs in the vicinity of doleritic intrusion¹⁹ (fig. 20), and the latter by the concentric structure in the slates in Ontario, which occur in contact with gabbro²⁰ (fig. 26). The texture of the intruded rocks, the intensity of the heating, the rate of the cooling, etc., may be the factors controlling the types of structure thus formed.

The stresses are tensional, especially for polygonal and columnar structure, but the horizontal joints which form tabular structure may be the result of shearing caused by the differential horizontal contraction of different parts of the columns during their cooling²¹. The stresses are probably tensions normal to the plane of the horizontal joints in the tabular structure.

¹⁸ Dale, T.N., The commercial granites of New England; Bull. 738, U.S.G.S., 1923, pp 32-33.

¹⁹ Beadnell, H.J.L., Columnar structure in the Nubian sandstone: Geol. Mag., vol. 63, 1926, pp 271-272.

²⁰ Leith, C.K., Structural Geology, revised ed., N.Y., 1923, pp 48-49.

²¹ Leith, C.K., op.cit., p 50.

Convection. * This is a crystallization process producing the columnar structure in some igneous rocks, and may be said to be complementary to the process of contraction. The explanation may be made briefly as follows: When a molten magma forms horizontal sheets after extrusion or intrusion the heat is lost from its upper portion (or is gained from its lower portion). If the top surface is cooler than the lower portion then the colder and denser parts at the top tend to sink and the warmer lower layer to rise, causing convection currents. If the conditions are constant and uniform, a steady state of flow will take place and take the form of parallel rising and descending currents. These currents will flow with minimum friction only when they divide the magma into polygonal cells (usually hexagonal.) If these cells succeed in leaving any permanent record of themselves when the magma sheet solidifies, then subsequent contraction may bring out the columnar structure by cracking the rock along the boundaries of the cells. In a lava in which different crystalline phases are separating at different temperatures, a certain amount of segregation is to be expected, and then the composition of the solid columns will show variations related to the convection cells. In some lavas the columns may be formed without segregation, and then will show no compositional variations but will nevertheless be symmetrical and regularly spaced.

The structure formed by convection is different from that formed by contraction in that the convection columns should be vertical or nearly so, much wider in proportion to their length, and hexagonal if perfect and also seven-sided or

pentagonal, with angles approximately 120° . The columnar structure in the Giant's Causeway is reported to belong to this type.²²

A differentiation accompanying convection might be expected to affect the cross-joints of the columns, thus resulting in the formation of tabular structure, and some types of concentric structure may have some connection with the convection process.

The boundaries between cells may constitute planes of weakness which localizes the joints due to subsequent contraction. In tabular structure the stresses may be tensional due to vertical contraction or may be shearing caused by differential horizontal contraction.

Hydration. This is an agency responsible for some types of concentric structure and probably promoting the polygonal crack structure. The process implies chemical decomposition of rocks. The action begins along surfaces and joints and makes its way very slowly into minute cracks and pores in the interior of rock blocks. Hydration tends to cause an increase in volume and hence results in a swelling of the part of the rock affected. This expansion of the outer hydrated part of the rock causes the concentric cracks. When the outer part of the rock block has been cracked into polygonal cracks by some other process, hydration develops in the inner part which retains moisture longer than the outside and results in expansion. Thus the exfoliation cracks are produced and the outer part of the rock tends to separate from

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²² Sosman, R.B., Types of prismatic structure in igneous rocks: Jour. Geol., vol. 24, 1916, pp 219-226.

the inner part.

Hydration occurs both in warm moist climates and in dry regions. The former, of course, are more favorable to the process. The concentric cracks in a boulder of diabase in the Sierra Nevadas of California may be cited as an example (fig. 24): But in dry regions during the dry season the sun quickly desiccates the outer side of the block, while the moisture remains on the shady underside for a much longer time and there continues the chemical work. The best examples were found in Owens Valley, California.²³

The process causes expansion, so the stresses applied are compressional and failure is apt to be due to shear tangential to the surface of the concentric crack. The stresses are probably greater than that required to pry rocks apart by tension though they are insufficient to break very strong rocks.

Other causes. These consist of the agencies which may cause or relate to the formation of some unimportant types of the mud-crack structure. They may be numerous, but the comparatively significant ones are solution, pressure and fire.

Solution and pressure are responsible for the stylolitic structure. The solution theory was suggested by Stockdale and Wagner and others. Stockdale's brief statement is the following.

"Stylolitic phenomena results from the differential chemical solution of hardened rock, under pressure, on the two sides of a bedding plane, lamination plane, or crevice, the undissolved portions of the

²³ Blackwelder, E., Exfoliation as a phase of rock weathering; Jour. Geol., vol. 33, 1925, pp 801-805.

one side fitting into the dissolved-out parts of the opposite, the interfitting taking place slowly and gradually as solution continues." ²⁴.

The pressure theory was advanced by Marsh and Quenstedt and others, and the explanation may be summarized as follows: Stylolitic displacement took place in the rock before consolidation was completed. A fossil would protect the muds below it, and the overlying material moving downward around it would form the column. When the columns stand out at right angles to the stratification, they have been produced by vertical pressure resulting from the weight of the superincumbent strata. The comparatively few stylolite-seams which have different positions are due to lateral pressure. But, in fact, any one theory does not explain all the phenomena shown by stylolitic structure. It is true, as stated by Dr Twenhofel, that the solution and pressure theories are dependent upon each other, the main elements of the solution-pressure theory being differential pressure, aided by solution acting at points of contact along a plane ²⁵.

Fire may be one of the agencies which causes some types of concentric structure or initiates some polygonal cracks. Forest fires are important and often act over vast areas. The effect of fire upon a rock mass is to expand the outer parts so suddenly that the tensile strength of the rock is exceeded radially and cracks are formed more or less parallel to the surface. But at the same time the polygonal cracks may be produced on the surface, vertically extending in-

²⁴ Stockdale, B.B., Stylolites, their nature and origin; Indiana University Studies, Study no. 55, 1922, p 46.

²⁵ Twenhofel, W.H., Treatise on sedimentation, 1st. ed., Baltimore, 1926, p 521.

ward, though the depth from the surface is commonly measured in centimeters. The two kinds of cracks cause the spalling off of plates or scales from the main rock blocks. The best example was found in the Medicine Bow Mountains of Wyoming, where the fire effects were shown on large boulder of quartzite²⁶. The stresses are compressional and likely to be tangential to the surface of the concentric cracks but normal to the plane of polygonal cracks.

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²⁶ Blackwelder, E., Fire as an agent in rock weathering; Jour. Geol., vol. 35, 1927, pp 134-140.

Fossil mud cracks and the significance of the mud-crack structure.

As stated in the foregoing chapters, mud-crack structure has been found in various sedimentary rocks. With the exception of those types recently formed in muds and those due to agencies other than desiccation, most, if not all, of the mud cracks in sedimentary rocks are ancient and may be called fossil mud cracks. They often furnish reliable evidence for determining the origin of the rocks in which they occur and the conditions under which they were formed. The useful records comprise not only the mud-crack structure originally formed in muds or soft deposits by desiccation but also other types of the structure which at times give clues for such determinations when found in fossil state, though their function is likely to be limited to certain conditions. The relations between the formation of the present mud-crack structure and the existing environments should be the same as in ancient times, and from the studies of the present conditions deductions can be made concerning the past.

Fossil mud cracks are commonly found in shales or argillites and also in fine-grained sandstones (on the one hand) and in limestones (on the other hand). From their preserved state it may be inferred that after the formation of the mud cracks there existed conditions which favored their preservation until the strata became buried, and allowed the cracks to

be filled with materials somewhat different from those composing the crack-bearing strata, so that the structure became distinguishable. Accordingly the existence of a fossil mud-crack forms a record to be interpreted not only in terms of the conditions favoring its formation, but also in terms of those favoring its preservation and distinctness. Furthermore, the variation in the form of the structure is useful in interpretative work; thus prolonged desiccation seems to favor the formation of columnar rather than polygonal structures. These considerations will now be discussed in more detail.

From present observations and experiments it appears that the preservation of mud cracks is controlled by the character of the mud or clay, the climatic conditions, and the topographic distribution. Silty clay is likely to be unfavorable for the preservation of a detailed mud-crack structure. The rapid swelling and disintegration of the surface stratum may destroy the formed structure. But when it remains moist, a little swelling and exfoliation may preserve the cracks. The structure in coarser rocks, such as the mud cracks in sandstone at Tunnel City, Wisconsin, might be formed in this way. Pure clays tend to retain its mud cracks upon rewetting either by rain or by flood and tidal water (fig. 27). On account of its tenacity such clay resists erosion even by quite rapid currents. If the cracks be filled with the same clay, the record of the structure would be blurred; if the sands be washed into the cracks, the structure would remain well defined. The mud cracks in the Mauch Chunk shale¹ may be cited as an example

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¹ Barrell, J., Origin and significance of the Mauch Chunk shale: Bull. G.S.A., vol. 18, 1907, pp 456-459.

of this type(fig 28). Limy mud, owing to its tenacity, is likely to be favorable for the preservation of mud cracks.They seem to resist tidal action and extend to a considerable depth forming columnar structure. The columnar structure of the limestone at Mount Wissick in Quebec² might be formed in this way(fig.17 and 18).

The mud cracks formed in pluvial climates are usually not well preserved and may be entirely obliterated,for the frequent rain does not give the formed cracks the chance for thoroughly drying and receiving filling materials. When rewetting by rain the cracks are closed, unless the material composing the deposits is so tenacious as to resist wilting. After a rainy period the deposits are again exposed to the sun and tend to crack,and the cracking often follows the trace of old cracks and results in a rude structure. But closely following rains will destroy it again,and even if preserved, the structure will not be a good and detailed one.

The semi-arid and arid climates are favorable not only for the development of mud cracks but for their preservation as well. During the dry season the mud cracks are well developed and the mud-cracked deposits are thoroughly desiccated and thus temporarily hardened. The hardening of the deposits may result in the structure being retained entirely,or at least partly,even under the action of flood water from heavy occasional rains. At the same time the flood water brings coarser material,such as sand,which it deposits in the cracks. This results sometimes in fairly conspicuous

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² Kindle,E.M.,Columnar structure in limestone:Can.Geol.Sur. Mus.Bull.,no.2,Geol.Ser.,no.14,1914,pp 1-5.

fossil mud cracks. The fossil sun cracks in the Shinarump shale in the Henry Mountains³ might be formed under this condition (fig. 9).

In playa lakes mud cracks are often well developed and also well preserved. Playas may be flooded with water partly from the outside by means of stream channels or by a general wash over the slopes, and partly from the inside by a gradual rise of the water level. In the first case the cracks are usually filled with sand which favors later recognition of the preserved structure; in the second case the clay settles in from quiet water, which tends to obliterate the cracks because of its similarity to the wall material of the cracks. The mud cracks on the margins of interior lakes may be preserved in the same way as in playas, and the wash of nearby land material and the action of waves may fill them with sand and thus lead to the formation of fossil structure.

The flood plains are most favorable for both the development and preservation of mud cracks. In the regions where the flood plains occur, the periods of desiccation are often seasonal and sufficient to harden the structure to such an extent that the next invasion of water does not wash it out, and the flood waters often sweep sand with them which fills up the cracks, thus preserving the mud cracks sometimes as very fine and extensive fossil structures, such as columnar mud cracks.

In the littoral zone the mud cracks are often destroyed by the plaining effect of the waves, and can only be

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³ Gilbert, G.K., Geology of the Henry Mountains: U.S. Geog. G.S., Rocky Mountain Region, 1880, p. 9.

preserved in the outer or upper zone. The mud-cracked deposits may be clay mud or limy mud, If they are clay mud, the cracks may not leave a record in the deposits unless the water brings some coarser material into them. This is uncommon because the material deposited in the cracks from the high tidal water is likely often to be as fine as that composing the mud-cracked deposits, thus leaving no distinct structure. If the sediments are limy muds, the cracks may be filled up with the clay somewhat different in composition from the limy mud, and hence the structure may be well preserved. The columnar structure of the limestone at Mount Wissick, Quebec,⁴ might be formed under the latter condition (fig. 17 and 18).

Fossil mud cracks are often used to infer the origin of the deposits in which they occur, the climatic conditions under which they were formed, and indirectly the topographic features. Some pre-Cambrian formations, such as the arenaceous and argillaceous deposits in Montana and Arizona, whose origin was in doubt, have been shown by the mud-cracked shales contained in them to be flood-plain deposits probably formed under semi-arid climates. The Mauch Chunk shale in Pennsylvania contains mud cracks with polygons having raised rims and concave surfaces. This indicates that the shale formation was formed on flood plains in semi-arid regions and not in marine waters, for the mud cracks formed in saline water do not have the surfaces of the polygons curved up. The limestones which contain mud cracks may be regarded as having been deposited in a littoral zone probably under semi-arid climates.

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⁴ Kindle, E.M., op.cit.

Frost cracks are another type of the mud-crack structure which has been found in fossil state. The fossil frost cracks in the Black Hills, South Dakota⁵, may be cited as an example (fig. 29). The structure was seen on some blocks of sandstone of late Mesozoic age. The cracks were slightly sunk below the surface and measured from one half an inch to four inches in length and from one-sixteenth to one-eighth of an inch in width. The appearance of the structure is quite unlike the ordinary mud-crack structure. It is deduced by Udden that the rocks which contain the frost cracks were formed during the period of transition between the Jurassic and the Cretaceous ages under shallow water conditions. That is, there might have been a change of climatic condition from tropical to temperate and during an age of such change the frozen mud flat containing the structure might occasionally have been buried under the sediments of an advancing tide.

Other types of the mud crack structure are not likely to be found in fossil state. It may be, however, that some of these types of mud-crack structure have been preserved and are now concealed in some parts of the formations in geological column. A consideration of the favorable environments for the occurrence of these fossil mud-crack structure suggests a search of the old surfaces, namely the unconformities or disconformities, and of the deposits on them, namely conglomerate formations or breccia beds. Most types of the mud-crack structure are of subaerial origin and some important and prevailing ones are due to weathering agencies, so that every old land surface was a

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⁵ Udden, J. A., Fossil frost cracks: Sci. Am., vol. 72, p 102.

place for their formation. A hiatus between formations, either an unconformity or a disconformity, represents a period of land formation. If the formed structure were not entirely eroded away before the land surface was covered by deposits, some trace of the structures should be found along the unconformable or disconformable contacts. Some types of the structure have been known to occur on boulders, blocks and pebbles. If they were not transported far enough to have their surface markings removed, and were accumulated to form permanent strata, the structure on them should be preserved with them and ascertained from the conglomerate and breccia beds.

By knowing the relations between the present climatic and topographic conditions and the mud-crack structure, the ancient climatic conditions and topographic features may be deduced from the fossil mud-crack structure found in consolidated formations. As frost cracks are commonly very large and found only in frigid regions, their recognition in fossil state would suggest that the place where they are found once had severe cold climates. If the mud-crack structure due to insolation be found in fossil state, the region where the fossil structure occurs may be considered as having been under rather tropical arid climates and elevated lands, while that due to congelation may be used to show that the region where it is found once had a rather cold moist climate and elevated lands. However, it is to be noted that such interpretations involve the difficult problem of distinguishing the structure due to insolation from that due to congelation. There appear to be no established and reliable data for making this distinction.

In general it seems that a structure due to insolation has irregular and nonuniform cracks and polygons and is usually not detailed and wide-spread, while that due to congelation has straight and equally spaced cracks and regular-sided polygons, forming a very fine polygonal network. Such a detailed structure, however, may be also formed by insolation, though it is more commonly due to congelation. Under cold-temperate climates congelation and insolation are cooperative. Hence it is probable that the rude mud-crack structures due to weathering agencies are due to insolation alone and signify a tropical climate, whereas the detailed structures are due to congelation or both congelation and insolation and signify a rather cold-temperate climate. Further, there is this criterion, that if the structure occurs on pebbles, boulders or blocks, the insolation cracks are likely to be only formed on the upside surface and not on the underside, while the congelating cracks may be developed any where on the surface of the pebbles, boulders or blocks.

The remainder of the mud-crack structures are either of igneous origin and thus independent of climatic and topographic conditions or due to other causes, which bear no definite relation to such conditions. Fossil polygonal cracks and concentric structure due to hydration signify rather temperate moist climates, but the same structure may be due to igneous effects. Accordingly these types of the mud-crack structure do not play an important role in geological interpretation.

Experimental study of mud cracks.

Many experiments have been conducted by Kindle and Doerr and are discussed in their papers. Some of their results may be regarded as conclusive evidence of certain relations between the formation of mud cracks and the conditions under which they are developed. But some of their experiments seem to give doubtful results and should be repeated; and some yielded quite different results in the hands of the different investigators. The writer's experiments here described include the repetition of the former experiments which gave doubtful or variable results, and the investigation of the character of mud cracks along some other lines. The materials used are two kinds of clays, one being a white-gray clay taken from the depth of about six feet below the surface at Madison, Wisconsin, and the other a brownish clay obtained from the experimental farm in Ashland; The apparatus consists merely of small pans of different sizes.

Experiment 1. Madison clay and Ashland clay were used. Equal amounts of each clay were put in separate pans of the same size (6.6 inches square) with the same amount of water (500 c.c.), and kept at the same temperature (72° F. average). In the pan containing the Ashland clay the water disappeared after 98 hours, when the cracking began, and continued to develop until 160 hours had elapsed when the mud was quite dry. In the pan containing the Madison clay the cracking started after 139 hours and continued until 196 hours had gone by when the

mud was dry and the cracking ceased. The object of this experiment was to get the characteristics of the cracks formed in different materials. The result was that the shape of the structure formed in the two kinds of mud was not different; but the cracks in Ashland mud were wider than those in Madison mud (figs. 30 and 31). Some polygons made up of Madison mud curled up at the margins in thin layers, while the polygons of Ashland mud showed greater warping up in the whole mass. According to tensile strength the Ashland clay is more tenacious than the Madison clay, so it is suggested that the more tenacious clays yield wider spaced mud cracks and polygons with more conspicuous warping up.

Experiment 2. Ashland clay was used to observe the effects of varying the amount of material, i.e., the thickness of mud plates. A mixture of one part ^{of} clay and three parts of water was put in a pan (4.2 inches x 2.4 inches), and a mixture of two parts of each was put in another pan of the same size. This means that the thickness of the mud in the first pan was smaller than that in the second pan. They were kept at an average temperature of 68° F. In the thin mud the cracking began after 90 hours and ceased after 110 hours when the mud was quite dry, but most of the cracks were formed during the time from 90 to 93 hours. In the thick mud the cracking started after 67 hours and continued for 9 hours, the cracks forming in the manner characteristic of advanced stages. The mud was quite dry after 120 hours. The period of the development of cracking in the thin mud was shorter than in the thick mud. The result is that the cracks in the thin mud were narrower and cut the mud into

smaller polygons than in the thick mud (figs. 32 and 33). The experiment was repeated several times. It may be concluded that the more thick the mud deposits, the wider are the cracks and the larger the polygons, other conditions being equal.

Experiment 3. The object of this experiment was to observe the effect of the physical composition of the material on the formation of mud cracks. Ashland clay, Madison clay and pure quartz sand were used, and the experiment was conducted in five pans of similar size. A mixture of one part of Ashland clay, one part of water and 20 grams of sand was put in the first pan; a mixture of one part Madison clay, one part of water and 20 grams of sand in the second pan; a mixture of one part of Madison clay, one part of water and 40 grams of sand in the third pan; a mixture of one part of Madison clay, one part of water, and 80 grams of sand in the fourth pan; and a mixture of 75% of sand and 25% of Madison clay with a suitable quantity of water in the fifth pan. They were kept in the same temperature, 70°F. average. In the first pan the cracking started after 64 hours and continued to develop until 86 hours had elapsed when the mud was thoroughly dry. The resulting cracks were not so regular as in pure clay mud. Most of them were tapering downward and did not extend down to the bottom of the pan. The surfaces of the walls of cracks were rough, and the polygons warped upward. The largest crack was about 3.2 millimeters in width (fig. 34). In the second pan the cracking commenced after 75 hours and ceased after 116 hours when the mud was quite dry. Most, if not all, of the cracks did not reach the bottom of the pan and were tapering downward. The walls of the cracks were rough, and the poly-

gons more or less curled up at the edges. The widest crack was about 3 millimeter on the surface(fig.35). In the third pan the cracking began after 76 hours along the margin of the mud plate and stopped after 108 hours. The cracks were mostly irregular,tapering downward and did not extend down to the bottom of the pan. The interesting phenomenon is that some fine cracks occurred in the middle portion of the surface of the polygons and did not extend outward to meet the larger cracks. This may be because the contraction was not sufficient to cause large, continuous cracks. The surfaces of the walls of cracks were very rough,and the greatest width of the cracks was about 2 millimeters(fig.36). In the fourth pan the cracking started after 66 hours along the margin of the mud plate and ceased after 102 hours when the mud was thoroughly dry. The cracks were very irregular with rough walls,tepering downward but not extending to the bottom of the pan. Some minor cracks did not continue to meet the major cracks. There were many small fine cracks which cut the surface layer of the mud without much sand,some starting out from big cracks,some being isolated. The largest crack was about 1.5 mm. in width(fig.37). In the fifth pan the cracking commenced after 92 hours,and there appeared to be a tendency toward parallel development. But after 106 hours when the mud was thoroughly dry,the structure was polygonal. Only the surface layer of the mud about 2mm.thick,without much sand,was cracked,and the polygonal plates strongly curled up, some parts being lifted up about 2cm. from the lower sand layer. The lower sand layer was not cracked. There were many small cracks cutting the surface part of the mud layer(fig.38).

From these results it may be concluded that the physical composition of the material affect the attitude of mud cracks; pure mud produces detailed and fine mud-crack structure, additions of sand gives the structure with narrower, shallower, tapering and irregular cracks, and an abundance of sand may prevent the formation of mud cracks. The tenacity of the clay depends on the relative amounts of the colloidal matter and the granular material. The more the colloidal matter and the less the granular material, the more tenacious is the clay and thus, the better developed the mud-crack structure. An addition of sand means a relative increase of granular material and thus a decrease of the tenacity of the mud. In other words, the amount of the colloidal matter in the clay has a very strong effect on the development of the mud-crack structure in that clay.

Experiment 4. The object of this experiment was to observe the effects of varying the salinity of the mud. It was conducted in two small pans. A mixture of 8 parts of Madison clay and 8 parts of water with one part of salt was put in the first pan and a mixture of equal amount of clay and water with half a tablespoonful of salt was put in the second pan. The first pan was kept at an average temperature of 72°F. After 12 hours there were formed many salt crystals scattered throughout the mud plate, and after the mud had dried no cracking occurred. The second pan was kept in the furnace with a temperature of 92°F. After 28 hours the cracking began and ceased after 40 hours when the mud was quite dry and the structure shown in fig. 39 resulted. The shape of the structure was not different from ordinary mud-crack structure, with the exception that the

structure was not very well developed and the polygons did not warp upward but remained flat. It may be concluded that in the mud with ordinary salinity the mud-crack structure has the polygons with a flat surface by which it may be distinguished from the structure in fresh mud which had polygons often with curled up surfaces, and that a high salinity of mud may prevent the formation of mud-crack structure.

Experiment 5. The object of this experiment was to obtain parallel mud cracks on an inclined surface. A mixture of one part of Madison clay and one part of water was put in a shallow pan. One side of the pan was raised five-eighths of an inch higher than the opposite side, so as to cause differential drying of the mud. The pan was kept at an average temperature of 70°F. After 68 hours the mud of the upper part was free from water, while the mud of the lower part was quite wet. At this time a big crack was formed which extended from one corner of the upper part to the wet part, but at the contact with the wet part changed its direction toward the side. After 70 hours another crack started from a corner of the lower part and extended to the upper part. Then a third crack began to occur at the middle of the upper part. After 74 hours there were formed many cracks which cut the mud plate into a network. The cracking continued until 100 hours had elapsed (fig. 40). The mud was thoroughly dry after 110 hours. It was found that the minor or subsequent cracks usually started from the curved part of the former major cracks. The experiment was repeated several times, but no parallelism of the cracks was observed. In his

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experiments Kindle¹ obtained parallel mud cracks which cut the mud into ribbon-like strips(fig.1). In this connection, it is to be noted that not only has the writer failed to produce parallel cracks, but also that the experiments of Dr Twenhofel² and Doerr³ did not show any tendency to form parallel mud cracks on an inclined surface. It would seem that the formation of parallel mud cracks involves some additional factors which just happened to be present in Kindle's experiment.

Experiment 6. The object of this experiment was to observe the relation between the formation of mud cracks and the rate of desiccation. In changing the rate of desiccation artificial temperatures and the action of the sun and wind were utilized. The experiment was performed in four stages under different conditions. A mixture of one part Madison clay and one part of water was put in the first pan and kept in a room with an average temperature of 72°F. A mixture of the same amount of clay and water was put in the second pan and kept outside under the action of the sun and wind, the temperature ranging from 42°F. at night to 90°F. in the daytime. The same mixture was put in the third pan and kept in a furnace with an average temperature of 92°F. The same mixture was put in the fourth pan and kept in a furnace with an average temperature of 220°F.(104°C:). In the first pan the mud started to crack after

¹ Kindle, E.M., Some factors affecting the development of mud cracks Jour. Geol., vol. 25, 1917, pp 137-139.

² Twenhofel, W.H., Treatise on sedimentation. 1st. ed., Baltimore, 1926, p 495.

³ Doerr, J.E., Theses, University of Wisconsin, 1924 and 1926

92 hours and was cut by cracks into polygonal blocks until 136 hours had elapsed when the mud was thoroughly dry(fig.41). The largest crack was about 3mm.in width. In the second pan the cracking began after 71 hours, and from 71-73 hours more than 10 cracks were formed. The mud was quite dry until after 94 hours. The main cracks were about 2.8mm wide(fig.42). In the third pan after 30 hours the water disappeared. The cracking began after 34 hours and ceased after 46 hours, when the mud was thoroughly dry. The largest crack was about 2.5 mm. in width(fig. 43). In the fourth pan the mud was quite dry after two hours. It contracted and dished upward. No big cracks were formed, but there were many small cracks and small pits on the surface. These small cracks were very like big mud cracks but only cut the surface layer of the mud. The cracks usually radiated out from a point in groups of three with nearly 120° angles between them. Several groups of the radiating cracks sometimes combined to form polygonal cracks(fig.44). According to the results of this experiment the time of desiccation was 44 hours for the first case, 23 hours for the second, 16 hours for the third, and less than 2 hours for the fourth. The cracks became narrower and narrower from the first to the fourth case, and in the last case the pattern of the structure was quite different. Hence it may be concluded that if other conditions are assumed to be equal, slow desiccation produces wide-spaced mud cracks, while rapid drying develops narrower mud cracks, and extraordinarily rapid desiccation affects the shape of the structure. But in his statement of the results Kindle⁴ concludes that rapid des-

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⁴ Kindle, E.M., op.cit., p 143.

iccation produces mud-cracks which are more widely spaced than those produced by slow desiccation. According to Doerr's⁵ experiments, slow desiccation produces mud cracks which are more widely spaced than those produced by rapid desiccation, and slow desiccation also produces larger polygons. The results of the three experiments include quite conflictive statements.

Experiment 7. The object of this experiment was to observe the effect of low temperature on the formation of mud cracks. A mixture of one part of Madison clay and three parts of water was put in a small pan, and another mixture of two parts of Madison clay and two parts of water was put in a pan of the same size. They were kept outside in the sun, the temperature ranging from 22° F. at night to 76° F. in day. The water was frozen after 6 hours and the mud contracted forming a very different structure which consisted of many minute cracks occurring throughout the surface of the mud. The minute cracks were often so arranged that one crack was nearly at right angles to the adjacent crack and many cracks were likely to form incomplete small rectangles or tetragons. After 70 hours when the temperature was 42° F. the ice was thawed, and the mud was still cracked but more or less disseminated, especially in the pan with more water. After 90 hours the mud was exposed to the sun at a temperature of 76° F. at noon, and the water was evaporated. After 102 hours the water disappeared and the mud-cracking began to occur and ceased after 120 hours when the mud was thoroughly dry. The cracks were very irregular and did not extend down to the bottom of the pan. The dimensions of the cracks and

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⁵ Doerr, J.E., op.cit.

polygons in the pan with more mud were larger than those in the pan with less mud. The largest crack in the thick mud was about 1.5 mm. in width and that in the thin mud about 1mm. wide. The difference in the size of the polygons can be seen from the figures 45 and 46. In this experiment the unique phenomenon was the formation of the minute cracks due to freezing of the mud. These cracks seem to be of the same type as the frost cracks described by Udden⁶. The shape of the minute cracks resembled the frost cracks in that they were straight and apt to taper to a point at one end, though the pattern of the structure was somewhat different from the frost-crack structure. It may be concluded that low temperature produces some type of frost cracks somewhat different from ordinary mud cracks in pattern and affects the mud-crack structure by forming an irregular appearance and causing an incomplete development.

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⁶ Udden, J.A., Fossil frost cracks: Sci Am., vol, 72, 1895, p 102.

Summary.

This paper contains a study of mud-crack structure. This term, as used here includes all the analogous and related structures, either in soft or hard and sedimentary or igneous rocks. These structures are all considered as forming one group because most of them are quite identical and have mutual relations, though some may be different in origin and in resulting form.

In the literature many terms are used to represent the mud cracks and their analogous and related structures. Some of them may be interchangeable; but most of them have their own distinctive applications. It is interesting to collect the related terms scattered in different papers together in order to compare them with each other and to re-define them somewhat more strictly. This review also shows that some terms are superfluous and may be dropped from consideration.

Many types of mud-crack structure are known. Some are formed in the incipient stage of the development of the structure, others are developed in advanced stages, still others either result from variations of the incipient structure or from complications that arise in advanced structures. Parallel polygonal, columnar and spheroidal structures seem to represent all the stages of the development of the structure from the simple to the complex. Each type may have its varieties, but in tracing the stages of the development, only the typical individual structures should be considered.

Mud crack structure occurs not only in soft deposits

such as mud and clay, but may also be found in many kinds of rocks, either sedimentary, metamorphic or igneous, and in some minerals and ice. Parallel structure is known in mud, sandstone, andesite, and granite; polygonal and columnar structures have been found in mud, clay, shale, sandstone, limestone, quartzite, marble, trachyte, phonolite, obsidian, diabase, dolerite, gabbro, basalt, volcanic mud, tuff, iron ore, quartz vein, coal, and salts, and ice; and the spheroidal structure is known to be present in shale, slate, quartzite, granite, andesite, obsidian, diabase and volcanic ash.

Climatic and topographic conditions are important factors affecting the development of the mud-crack structure. Most of the main processes which form the mud-crack structure vary in effectiveness with the climatic and topographic conditions, and, of course, the formation of the mud-crack structure depends upon the effectiveness of the processes. Well developed structures in soft deposits are commonly found in regions with temperate semi-arid climates and lower topography, and occasionally in temperate arid or tropical intermittently rainy regions. The mud cracks due to frost action occurs in frigid regions. The structure in hard rocks due to congelation is likely to be present in temperate rainy regions with high relief, while that due to insolation is well developed in torrid arid regions and in temperate arid elevated regions.

There are many processes and causes which control the formation of mud-crack structure. The important ones are desiccation, insolation, congelation, contraction, convection and

hydration. They may be divided into two main groups, namely, weathering or exo-destructive agencies and igneous or endo-destructive agencies. The former includes desiccation, insolation, congelation and hydration which act on the substances from the outside; and the latter includes contraction and convection which are internal actions. The stresses are mostly due to contraction and thus chiefly tensional, Those due to expansion are, of course, compressional.

Mud cracks are known to occur in fossil state in shales, sandstones, and limestones, either as polygonal or as columnar structures. The character of the mud, the climatic conditions and the topography are important factors affecting the preservation of the mud cracks. Frost cracks have also been found as fossil structures, and other types of the mud-crack structure are supposed to have been preserved in the formations in the geological column. Any type of the fossil structure may be used to interpret the origin of the rocks in which it occurs and the climatic and topographic conditions under which it was formed.

Several experiments on the formation of the mud cracks were performed. The results are mostly coincident with those of former investigators, but some are somewhat different, and some are new. The effects of low temperature, rate of desiccation, physical composition of the material and salinity of the mud are most interesting, and other experiments also gave results showing the control of other factors on the development of mud cracks. It is a matter of regret that lack of time did not permit experiments to be made on the mud-crack structure in hard rocks.

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Fig.1. Parallel mud cracks cutting the mud into ribbon-like strips. $\frac{1}{4}$ natural size.(after Kindle).

Fig.2. Parallel cracks in an andesite pebble in the desert of Tumbes, Northwest Peru.(after Brown).

Fig.3. Sheet structure in granite at Dell Hitchcock Quarry, Quincy, Mass. (after Dale).

Fig.4. Sheet structure with vertical joints at Northwest Wall of Longfellow Quarry, Hallowell, Maine. (after Dale).

Fig.5. Frost cracks in the Canning River Region, northern Alaska. (after Leffingwell).

Fig.6. Mud cracks, Nile flood-plain, sufficiently wide and deep to admit a man's arm to the elbow. (after Grabau).

Fig.7. Mud cracks with polygons 1' to $\frac{1}{2}$ ' in diameter, Miami, Florida. (after Kindle).

Fig.8. Mud cracks with polygons having terrace-like margins, Miami, Florida. (after Kindle).

Fig.9. Fossil sun-cracks in the Shinarump shale,
Henry Mountains. (after Gilbert).

Fig.10. Polygonal structure on a bedding plane of the Twentymile sandstone in the Twenty-mile Park District, Colorado. (after Campbell).

Fig.11. Polygonal structure on the edge of the Trout Creek sandstone bed. (after Campbell).

Fig.12. Polygonal cracks on a sandstone pebble
in the desert of Tumbes, Northwest Peru.
(after Brown).

Fig.13. Polygonal cracks on a sandstone pebble
with one crack along the bedding plane in
the desert of Tumbes, Northwest Peru.
(after Brown).

Fig.14. Weather-crack structure on the surface of a diabase boulder, Pennsylvania. (after Sosman).

Fig.15. Polygonal cracks on a diabase boulder, Montgomery County, Pennsylvania. (after Wherry).

Fig.16. Polygonal structure on the surface of a diabase sill, west of Philadelphia, Pennsylvania. (after Sosman).

Fig.17. Blocks of limestone showing columnar structure, Temiscouata Lake, Quebec. (after Kindle).

Fig.18. Columnar structure in limestone, Temiscouata Lake, Quebec. (after Kindle).

Fig.19. Polygonal and columnar structure in a cement briquette, caused by internal expansion. (after Sosman).

Fig.20. Columnar structure in Nubian sandstone,
Wadi Kreiga, Red Sea Coast, Egypt. (after
Beadnell).

Fig.21. Columnar structure in the basalt
of the Giant's Causeway, Coast of
Ireland. (after Grabau).

Fig.22. Stylolites in the Muschelkalk,
Germany. (after Stockdale).

Fig.23. Large, perfectly formed stylolites
of the Salem limestone, Lawrence County,
Indiana. $\frac{1}{6}$ natural size. (after Stockdale).

Fig.24. Exfoliation-crack structure in a diabase boulder, Sierra Nevada, California. (after Blackwelder).

Fig.25. Polygonal cracks on a granite boulder, indicating the relation to concentric cracks, Owens Valley, California. (after Blackwelder).

Fig.26. Concentric structure in slate, Cobalt District, Ontario. (after Leith).

Fig.27. Mud cracks which have been covered by two or more tides, Black Rock, N. S. (after Kindle).

Fig.28. Fossil mud cracks in the Mauch Chunk shale,
Pennsylvania. (after Barrell).

Fig.29. Fossil frost cracks on sandstone,
Black Hill, South Dakota. (after Udden).

Fig.30. Mud cracks formed in the Ashland clay mud,
showing wide-spaced cracks.

Fig.31.Mud cracks formed in the Madison clay mud,
showing cracks narrower than those in the
Ashland clay mud.

Fig.32. Mud cracks formed in thin mud.

Fig.33. Mud cracks formed in thick mud.

Fig.34. Mud cracks formed in the Ashland clay mud with 20 grams of quartz sand.

Fig.35. Mud cracks formed in the Madison clay mud with 20 grams of quartz sand.

Fig.36. Mud cracks with fine cracks formed in the
Madison clay mud with 40 grams of quartz sand.

Fig.37. Mud cracks with fine cracks formed in the
Madison clay mud with 80 grams of quartz sand.

Fig.38. Mud cracks formed in a mixture of 75% of sand and 25% of Madison clay, showing curling up of upper mud layer and lower sand layer not cracked.

Fig.39. Mud cracks formed in saline mud, showing not well-developed structure and flat polygons.

Fig.40. Mud cracks formed on an inclined mud plate, showing the minor cracks starting out from the curved part of the major cracks.

Fig.41. Mud cracks formed at a temperature of 72° F. in room (formed by slow desiccation).

Fig.42. Mud cracks formed at temperatures from 42° to 90° F. outside under the action of the sun and wind.

Fig.43. Mud cracks formed at a temperature of 92° F. (in furnace).

Fig.44. Small cracks formed at a temperature of 220° F. (104° C., formed by very rapid desiccation).

Fig.45. Mud cracks formed at low temperature
in thick mud.

Fig.46. Mud cracks formed at low temperature in
thin mud.

Approved:

C. K. Lenth

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